Jagdish Chander Dagar
Sharda Rani Gupta
Demel Teketay *Editors*

Agroforestry for Degraded Landscapes

Recent Advances and Emerging Challenges - Vol. 2

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Prologue

Agroforestry technologies can be applied to rehabilitate or restore degraded lands from agriculture, soil erosion, deforestation, rangeland degradation, mining sites, and over-extraction at various scales, from plot to farm level to large agricultural and degraded landscapes. In North America and other temperate zones, riparian buffers, alley cropping, windbreaks, silvopasture, and forest farming are some of the major agroforestry practices. Agroforestry has both productive and service functions; for example, a range of products, including fuelwood, fodder, timber, and medicinal products, serve to diversify the outputs from agroforestry systems. Agroforestry systems also provide a variety of regulating environmental services including carbon sequestration, soil fertility improvement, reducing soil erosion, regulating water regimes for rural producers and urban consumers, providing habitat for pollinators and seed dispersers, climate regulation, and biodrainage. The research in both tropical and temperate regions has shown that introduction of agroforestry practices on degraded landscapes can provide significant benefits in terms of provisioning and regulating services. Generally, agroforestry increases delivery of regulating ecosystem services within the landscape, leading to increased production from crops and animals. Agroforestry systems have favorable effects on soil properties and processes, which play an important role in climate regulation through carbon sequestration and reducing greenhouse gas emissions and provision of water through regulation of soil properties. Soil improvement in agroforestry systems is linked to biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, building up of soil organic matter from aboveground and belowground parts of plants, increasing soil microbial activity, improving soil enzyme activity, and enhancing activity of arbuscular mycorrhizal fungi.

In Volume II, the topics covered primarily deal with agroforestry technologies that have been applied to rehabilitate degraded lands from agriculture, soil erosion, deforestation, rangeland degradation, mining sites, and over-extraction at various spatial scales. Agroforestry options have been found practicable in rehabilitation and biological reclamation of degraded lands prone to water and wind erosion including sand dunes; acid sulfate soils of humid regions characterized by low pH, toxicity of aluminium and iron, and deficiency of nutrients; salt-affected sodic and saline soils; and waterlogged saline soils. For checking wind erosion, windbreaks and shelter belts involving appropriate species which require less water and possess deep root system have been established in drylands; the trees and shrubs play a major role in improving the efficiency of nutrient cycling in the system. Disposal of urban waste, especially sewage water, needs attention in all the countries. The role of agroforestry for promoting and judicious utilization of all kinds of biodiversity, climate change mitigation and adaptation, improving soil fertility, enhancing carbon sequestration, and improving livelihood security have been discussed.

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

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

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Part I

Temperate Agroforestry

1 Biomass Production Potentials Under Temperate Agroforestry Systems as Influenced by Selected Sustainability Indicators: A Case Study Approach with Supportive Evidence

N. V. Thevathasan, A. B. Bazrgar, A. M. Gordon, S. Silim, R. Y. Soolanayakanahally, B. Coleman, and M. W. Ashiq

Abstract

The research data presented in this chapter are from two long-term ecological research sites managed by the University of Guelph's agroforestry research and development team. One of these sites is a tree-based intercropping site close to the University, and the other is an integrated riparian management site, located at Washington Creek, Ontario, Canada. In this chapter, we have included the analyses of several sustainability indicators that were measured from these long-term ecological research studies conducted at the above sites. We have used them as evidence to support sustainable production of biomass in temperate agroforestry systems. The selected sustainability indicators are soil carbon (C), soil quality, system-level C sequestration, biodiversity, water quality, nutrient cycling and availability, other components of the biophysical environment, and potential greenhouse gas reduction mechanisms. The chapter discusses these

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sustainability indicators and their influence on biomass production. At the production level, the underlying assumption is that maintenance of these sustainability indicators above a given threshold level should contribute to continuous sustainable biomass production. Among temperate agroforestry systems, riparian buffer plantings have the greatest potential to produce biomass while enhancing biodiversity, and environmental and ecosystem services. The reason for this is that the tree density in riparian plantings can be substantially increased over other types of agroforestry systems, since there are no associated annual crops grown under the plantings. In addition, as they are established at the terrestrial-aquatic interface of both lakes and streams, competition for moisture is seldom a limiting factor. They also exert a disproportionate regulatory influence over many important ecological processes—both terrestrial and aquatic in nature—at many scales. In tree-based intercropping systems, short-rotation woody crops (SRWC) or herbaceous biomass crops can be grown in between the tree rows. Along the tree rows, however, high-value timber trees can be grown for long-term economic benefits with the SRWC grown in the alleys to generate short-term revenues from biomass production while contributing to environmental services as described in this chapter.

Keywords

Biodiversity · Carbon sequestration · Ecosystem services · Greenhouse gases · Intercropping systems · Riparian buffer

1.1 Introduction

The modernization of Canadian agriculture in the past 150 years has resulted in, as in the other parts of the world, environmental problems such as increased soil erosion from both wind and water vectors, declining crop productivity on marginal lands, loss of habitat for native animals and plants, and enhanced nutrient loadings into streams draining agricultural areas with subsequent effects on water quality and quantity. In addition, a host of socioeconomic problems has emerged in tandem with these—loss of the family farm with a concurrent increase in the size and number of industrially sized farm operations, loss of income diversity, and changes in rural community structure. These problems are not unique to specific regions in Canada, although depending upon the nature and combination of regional soils and climates may be more prevalent in particular areas.

Our early agricultural ancestors, while adamant about clearing land for agricultural practices, were also cognizant of the important roles that trees could play in sustaining farm systems, and although they didn't practice agroforestry per se, they did have an appreciation for products and services that could be derived from on-farm trees. In recent years, trees grown in various agroforestry systems are also being considered as a potential source of biomass for bioenergy production (Coleman et al. 2019; Lutes et al. 2019; Cardinael et al. 2012; Clinch et al. 2009).

Table 1.1 Summary of research on various agroforestry systems undertaken in southern Ontario, Canada

Agroforestry system	Reference
Windbreaks or shelterbelts	Kenney (1987); Loeffler et al. (1992)
Riparian buffer agroforestry systems	O'Neill and Gordon (1994); Oelbermann and Gordon (2000 and 2001); Oelbermann et al. (2015 and 2008); De Carlo et al. (2019); Oelbermann and Raimbault (2014)
Forest farming systems	Matthews et al. (1993); Christrup (1993); Williams et al. (1997)
Tree-based intercropping systems	McLean (1990); Ball (1991); Gordon and Williams (1991); Williams and Gordon (1992, 1994, and 1995); Ntayombya (1993); Ntayombya and Gordon (1995); Thevathasan and Gordon (1995 and 1997); Thevathasan (1998); Price and Gordon (1999); Dyack et al. (1999); Price (1999); Simpson (1999); Zhang (1999); Howell (2001); Cardinael et al. (2012); Gibbs et al. (2016); Peichl et al. (2006); Wotherspoon et al. (2014); Bambrick et al. (2010); Evers et al. (2010); Jefferies et al. (2014); Borden et al. (2014); Oelbermann et al. (2006)
Silvipastoral systems	Bezkorowajnyj et al. (1993)
Purpose-grown woody biomass production system	Cardinael et al. (2012); Ashiq et al. (2018); Dias et al. (2017); Lutes et al. (2016 and 2019); Marsal et al. (2016); Coleman et al. (2019); Clinch et al. (2009), Bazrgar et al. (2020)

Agroforestry is an approach to land use that incorporates trees into farming systems and allows for the production of trees and crops or livestock from the same piece of land in order to obtain economic, ecological, environmental, and cultural benefits (Thevathasan et al. 2018; Gordon et al. 2018). Agroforestry has its roots in the developing world, where lack of land resources in the presence of high population growth necessitated the development of novel systems of simultaneous wood and food production by indigenous peoples. In United States of America and Canada, many types of agroforestry have been employed historically (Thevathasan et al. 2012, 2018), but the vast potentials for economic and environmental benefits attributed to agroforestry have yet to be realized on a large scale. The main types of agroforestry practices currently being researched in many areas of Canada are windbreaks or shelterbelts, silvipastoral systems [animals, pasture, and trees], riparian buffer agroforestry systems, forest farming systems, purpose-grown woody biomass production systems, and tree-based intercropping systems [crops grown between widely spaced tree rows] (Thevathasan et al. 2012, 2018; Gordon et al. 2018; Garrett et al. 2000). These systems have also been extensively researched in southern Ontario, Canada, and are summarized in Table 1.1.

This chapter will present results from two case studies in southern Ontario, Canada, with special reference to tree-based intercropping and riparian buffer agroforestry systems. It will also document potential environmental sustainability indicators that could be adopted as a measure of assessing ecosystem health in these given systems. Trees can be harvested for biomass from these systems as long as the measured sustainability indicators are maintained at the system level.

1.2 Biomass Production in Tree-Based Intercropping Systems and Associated Environmental Benefits

The biomass yield from any agroforestry systems in Canada will directly depend on the tree density, tree species, soil, latitude, associated intercrop, and environmental conditions. In tree-based intercropping systems, short-rotation woody crops (SRWC) or herbaceous biomass crops can be grown in between tree rows. In addition, tree densities can also be varied and harvested at different time intervals in order to optimize biomass production.

Studies at the French National Institute for Agricultural Research (INRA) have identified three distinct tree-based intercropping systems based on tree densities per hectare (Dupraz and Liagre 2008). These intercropping systems are:

(a) Stable agroforestry (20 to 50 trees ha^{-1}), where crops can be grown until tree harvest. To have a stable agroforestry system, the distance between two tree rows should be at least twice the height of adult trees (30 to 40 m).
(b) Changing agroforestry (50 to 200 trees ha^{-1}), where at the end of tree growth, crop area may be reduced or one will have to grow shade-tolerant crops.
(c) Ephemeral agroforestry (more than 200 trees ha^{-1}), where one can grow crops only during the first few years.

Trees can also be harvested for biomass and be replanted so that herbaceous biomass or annual crops can be grown in order to optimize space utilization. The data presented in this report were obtained from the University of Guelph's SRWC research site where willow (*Salix discolor*) clones were grown as an intercrop. Therefore, this study was conducted in a "changing agroforestry" system with a tree density of 111 trees ha^{-1}. During the early stages, annual crops were grown in the alleys. Due to the current interest in biomass for bioenergy, we utilized willow as an alternative crop that could be successfully grown in the alleys of a mature (21-year-old) tree-based intercropping system. This is a new temperate agroforestry concept – trees within trees – but willow is considered a crop due to the short harvest cycle of 3 years.

Past studies (Thevathasan and Gordon 2004; Reynolds et al. 2007; Clinch et al. 2009) on the same site have clearly demonstrated complementary growth-promoting interactions in the middle of cropping alleys as influenced by the presence of mature trees along the tree rows (Fig. 1.1).

It appears that these growth-promoting interactions or processes have positively enhanced willow biomass yield in the agroforestry site when compared to the yield from the monocropping site (no mature trees) (Table 1.2) (Diagrammatic sketch credit: Rachelle Clinch).

The willow clonal varieties *Salix dasyclados* (SV1) and *Salix miyabeana* (SX67) produced the highest yields overall (Table 1.2), and they may be recommended as promising biomass crops to be incorporated both in tree-based intercropping fields and in open fields. It is also important to note that such high biomass yields were obtained with only 15 kg nitrate-N ha^{-1} (soil mineralization measured in both fields

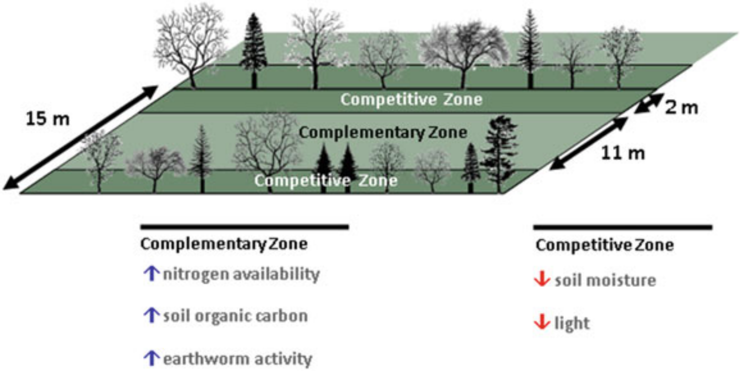


Fig. 1.1 "Competitive" and "complementary" zones in a mature tree-based intercropping system in southern Ontario, Canada

Table 1.2 Biomass yields of three willow clones, 3 years after coppice. Values represent means. Values followed by the same lowercase letter are not significantly different based on Tukey's HSD test ($p > 0.05$), within a site

Field and clone	Willow biomass (odt ha^{-1} y^{-1}) (odt = oven dry ton)
Agroforestry	4.86[a]
9882-41	2.82b
SV1	5.64 ac
SX67	6.12a
Control	3.02[a]
9882-41	2.24b
SV1	4.50c
SX67	2.31b

Values represent least squares means where those with the same letter are not significantly different according to Tukey's HSD test ($p > 0.05$)
[a]Field averages are significantly different ($p < 0.05$)

in June 2009—data not presented). This suggests that willow biomass crop can be grown without external inorganic fertilization at least during the initial years of establishment. As expected, root biomass followed a similar trend as observed in above-ground biomass yield. Root systems were more developed in the agroforestry field when compared with the control site (Fig. 1.2).

It is believed that site-specific parameters not measured in this study but measured on these sites by other researchers, such as sub-surface hydrology (Clinch et al. 2009), may have contributed to above- and belowground biomass yield differences. In addition, the fine roots comprised a surprisingly large percentage of the total root biomass. Studies of hybrid poplar have shown that fine root biomass accounts for up to 60% of the total root biomass in 1-year-old trees (Dickman and Pregitzer 1992), about 40% of the total root biomass in 2-year-old trees (Friend et al. 1991), and 21–40% of the total root weight in a 4-year-old hybrid poplar (Heilman et al. 1994).

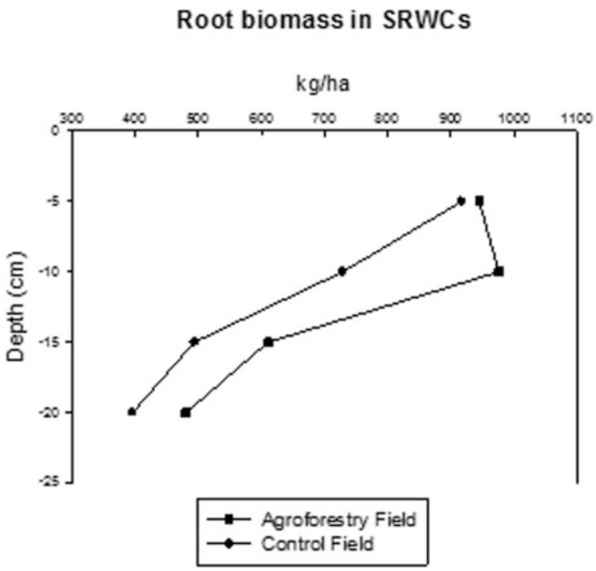


Fig. 1.2 Willow root biomass distribution in the agroforestry field and monocropping field, 3 years after coppice in 2009, southern Ontario, Canada (Adapted from Cardinael et al., 2012)

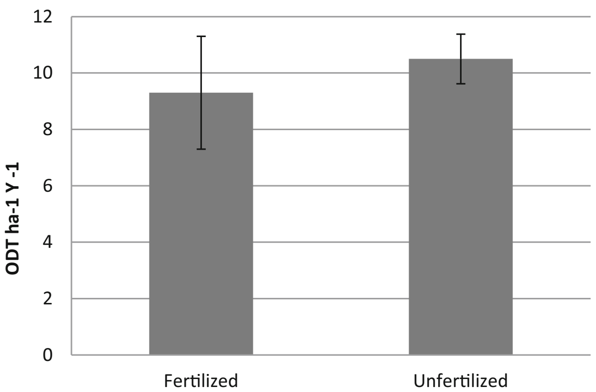


Fig. 1.3 Willow biomass yields as influenced by fertilization in 2012 (second harvest) at the University of Guelph Agroforestry Research Station, Guelph, Ontario, Canada

Based on these results, it was estimated that fine root biomass turnover was about 40% of total root biomass, i.e., 1200 kg ha^{-1} y^{-1} in the agroforestry field and 1000 kg ha^{-1} y^{-1} in the control field.

Biomass yields reported above are considered below average, and this should be expected during the initial establishment stage. It is a challenge to establish any biomass crops mainly due to climatic year-to-year variations and weed control issues. However, when established fully, in 2 to 3 years, subsequent harvest yields gradually increase. The willows at the University of Guelph research site were planted in 2006, and yields reported above are from the first harvest. Biomass yields during the second harvest (2012) significantly increased and are presented in Fig. 1.3.

From Fig. 1.3, it appears that fertilizer application at the rate of 151 kg ha^{-1} N every 3 years did not influence willow biomass yields in agroforestry and monocrop systems. The yields presented in Fig. 1.3 are an average from both production systems. As stated above, fertilizer application during the early years of growth of biomass crops may not provide any yield increases or additional economic returns.

In 2012, at the same research site, mature intercropped trees (three trees per species) of five species [poplar (*Populus* spp.), walnut (*Juglans nigra*), red oak (*Quercus rubra*), Norway spruce (*Picea abies*), and white cedar (*Thuja Occidentalis*)] were destructively harvested to estimate their respective biomass production potentials. At the time of harvest, all trees were 26 years old. Table 1.3 documents biomass quantification values for each tree species broken down by their components.

The numbers presented in the above table represent mean values from three trees; therefore, if we know the density of trees per hectare, total biomass production can be calculated. From Table 1.3, poplar has the greatest potential to produce the largest amount of biomass. However, as hybrid poplars are short-lived (25 years or less), management strategies should be put in place to harvest and replant at different time intervals in order to ensure continuous production of biomass over a time period. Other tree species also have the potential to produce biomass, but as they are slow-growing trees, they have the greatest potential to sequester C over a period of time and also allow to produce other sources of biomass such as SRWC and herbaceous biomass in the alleys between two tree rows.

1.2.1 Biodiversity

Biodiversity has become a widely used sustainability indicator to assess any given ecosystem health and function. Several biodiversity indices such as species richness, Shannon-Wiener index, etc. are used to describe biodiversity in quantitative terms. It is also safe to say that the birth of modern agriculture coupled with intensive use of pesticides and fertilizers has resulted in a lack of diversity in agro-ecosystems. However, agroforestry systems contribute toward agroecological principles and thus enhance biodiversity. At the University of Guelph tree-based intercropping system research site, a few studies were conducted to assess its system diversity, and results obtained are given below.

1.2.1.1 Bird Diversity

The practice of tree-based intercropping adds a third vertical dimension, absent in conventional agricultural fields, to the land base, which helps to modify microclimatic parameters (discussed below) while at the same time providing habitat for small animals and birds.

A study was conducted on-site by Williams et al. (1995) to investigate the bird use of an intercropped cornfield, a conventional cornfield, and an old-field site. The old-field site was comprised of various tall grasses and weeds including goldenrods (*Solidago* spp.), asters (*Aster* spp.), and milkweeds (*Asclepias* spp.). Only one

Table 1.3 Biomass and carbon content (mean + standard deviation) of different tree components from five tree species in a 25-year-old intercropped system in southern Ontario, Canada ($n = 3$ per species, ± standard deviation) (Adopted from Wotherspoon 2014)

Poplar	Dry biomass (kg)	C concentration (%)	C content (kg)
Trunk	196.30 ± 61.93	51 ± 29	99.99 ± 2.62
Primary branches	91.84 ± 63.23	53 ± 32	48.06 ± 1.21
Secondary branches	48.33 ± 40.83	53 ± 21	25.44 ± 2.14
Twigs	25.86 ± 4.59	53 ± 2	13.65 ± 0.03
Roots	102.63 ± 54.44	50 ± 32	52.33 ± 2.18
Total tree	464.95		239.46 (± 61.71)[c]
Red Oak	**Dry biomass (kg)**	**C concentration (%)**	**C content (kg)**
Trunk	102.55 ± 20.09	52 ± 12	53.33 ± 2.03
Primary branches	31.57 ± 11.06	49 ± 5	15.53 ± 1.02
Secondary branches	24.04 ± 10.70	49 ± 5	11.53 ± 5.36
Twigs	45.33 ± 11.98	51 ± 6	22.99 ± 2.20
Roots	73.94 ± 10.01	48 ± 5	35.79 ± 0.27
Total tree	277.43		139.42 (± 22.41) [bd]
Black Walnut	**Dry biomass (kg)**	**C concentration (%)**	**C content (kg)**
Trunk	118.03 ± 17.27	52 ± 10	61.01 ± 2.10
Primary branches	33.98 ± 13.86	50 ± 7	17.19 ± 1.90
Secondary branches	18.56 ± 7.07	51 ± 3	9.36 ± 1.62
Twigs	41.41 ± 22.20	50 ± 11	20.60 ± 0.24
Roots	52.76 ± 38.47	47 ± 18	24.25 ± 2.91
Total tree	264.75		132.42 (± 49.65) [d]
Norway Spruce	**Dry biomass (kg)**	**C concentration (%)**	**C content (kg)**
Trunks	67.60 ± 24.83	52 ± 13	35.36 ± 19.97
Branches	39.85 ± 22.87	53 ± 13	21.24 ± 1.96
Twigs	20.95 ± 6.00	53 ± 3	11.01 ± 0.84
Needles	33.19 ± 17.42	53 ± 9	17.57 ± 1.13
Roots	61.48 ± 29.20	52 ± 16	32.04 ± 0.54
Total tree	223.07		117.22 (± 44.39) [abd]
White Cedar	**Dry biomass (kg)**	**C concentration (%)**	**C content (kg)**
Trunks	36.94 ± 23.01	52 ± 13	19.49 ± 2.30
Branches	5.78 ± 5.97	53 ± 3	3.04 ± 0.59
Twigs	9.67 ± 6.28	53 ± 3	5.09 ± 0.49
Needles	22.89 ± 9.30	53 ± 5	12.14 ± 0.32
Roots	18.62 ± 3.65	47 ± 2	8.83 ± 0.88
Total tree	93.90		48.60 (± 24.81) [a]

species of bird nested in the conventional cornfield, and the avian diversity in the intercropped area (ten species) was similar to that found in old-field site (six species). In addition, more bird species foraged in the intercropped plots (ten species) compared to the conventional cornfield (two species) and old-field site (six species). Results from the bird survey are presented in Table 1.4.

Table 1.4 Number of birds observed foraging in intercropped, maize-only, and old-field plots at Guelph, Ontario, Canada (Thevathasan and Gordon 2004)

Bird species	Intercrop	Maize field	Old field (abandoned field)
Song sparrow (*Melospiza melodia*)	0	0	12
Eastern kingbird (*Tyrannus tyrannus*)	0	0	6
Tree swallow (*Tachycineta bicolor*)	12	2	2
Red-winged blackbird (*Agelaius phoeniceus*)	2	0	17
Savannah sparrow (*Passerculus sandwichensis*)	20	0	15
Horned lark (*Eremophila alpestris*)	2	2	0
Eastern meadowlark (*Sturnella neglecta*)	0	0	2
Eastern bluebird (*Sialia sialis*)	8	0	0
American robin (*Turdus migratorius*)	2	1	0
Killdeer (*Charadrius vociferus*)	4	1	0
American goldfinch (*Carduelis tristis*)	12	0	0
Indigo bunting (*Passerina cyanea*)	3	0	0
European starling (*Sturnus vulgaris*)	16	0	0
Total species	10	4	6

The study revealed that intercropping provided opportunities for birds to nest and forage that were not available in the monocropped maize field. The diversity of the breeding population in the intercropped field approached that found in the nearby old-field site, although some of the species were different. The intercropped field also provided foraging opportunities for other species whose diversity and numbers clearly demonstrated the value of the site to local and migrating bird populations.

1.2.1.2 Plant Diversity

The species richness values were highest in the agroforestry field with 8.375, followed by 5.5 for the nearby forested site and 2.5 for the adjacent agricultural field. Detailed list of assessed plants are not presented in this report, but biodiversity indices can be effectively used as a reliable sustainability indicator to verify sustainability of biomass production in agroforestry systems.

1.2.1.3 Insect Diversity

Studies on arthropod abundance and diversity at the University of Guelph's tree-based intercropping site showed that taxons such as the Opiliones, Dermaptera, and Carabidae, which are associated with organic litter and areas that provide shelter during the day, were significantly higher in the intercropped system than in the monoculture system (conventional agricultural system). Significantly higher numbers of parasitoids and detritivores were also recorded in the intercropped system compared to the monoculture system; the intercropped treatment also supported a significantly higher ratio of parasitoids to herbivores (Fig. 1.4). We surmise that trees grown with crops such as maize or any biomass crops may improve insect pest management options by providing habitat that will foster populations of natural enemies (Middleton

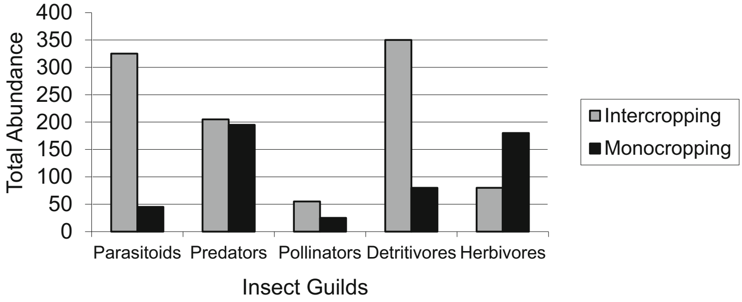


Fig. 1.4 Total arthropod abundance in June samples (1999) in the tree-intercropped plots (12-year-old trees) and sole crop sites, Guelph, Ontario, Canada (Adapted from Thevathasan and Gordon 2004)

Table 1.5 Comparison of total mean earthworm numbers (no. m^{-2}) and biomass (g m^{-2}) under an intercropped system and a conventionally cropped corn system at the University of Guelph Agroforestry Research Station, Guelph, Ontario, Canada (Adapted from Thevathasan et al. 2004)

	Numbers (no. m^{-2})				Biomass (g m^{-2})			
	Poplar	Maple	Ash	Corn	Poplar	Maple	Ash	Corn
1997								
Spring	394a (a)	257a (b)	379a (a)	11a (c)	457a(a)	440a (a)	735a (b)	6.07a(c)
Summer	119b (a)	42b(b)	61b(b)	4a(c)	245b(a)	89b(b)	153b (b)	4.54a(c)
Fall	257c (a)	196c (a)	268c (a)	30b (b)	345c (ab)	263a (b)	437c (a)	45.96b (c)
1998								
Spring	90b(a)	63b(a)	46b(a)	3 a(b)	181b(a)	144b (a)	161b (a)	3.12a(b)

Values followed by the same letter within a column are not significantly different (LSD, $p < 0.05$)
Values followed by the same letter across a row, within brackets, are not significantly different (LSD, $p < 0.05$)

2001). More specific research on these aspects is required in order to obtain a good understanding on integrated pest management (IPM) dynamics in this system.

1.2.1.4 Earthworm Diversity

Agroforestry land-use systems are often credited for their role toward increasing soil organic matter and carbon (C). Higher soil organic matter and low soil disturbance can increase the presence and activity of soil fauna, particularly invertebrates such as earthworms (Edwards and Lofty 1977). A study of earthworm population dynamics in a temperate intercropping system was undertaken at the University of Guelph Agroforestry Research Site in 1997 and 1998 (Price and Gordon 1999). Tree species played an important role in determining the spatial and temporal distribution of earthworms within the intercropping system. Significant differences ($p < 0.05$) in earthworm density and biomass were observed between sampling periods and tree species (Table 1.5). For example, earthworm densities in poplar (*Populus* spp.) and ash (*Fraxinus americana*) tree rows were greater than those in silver maple (*Acer saccharinum*) or corn (*Zea mays*), possibly due to greater litter contributions or more rapid decomposition of leaf litter or both. Earthworm numbers decreased during the summer period, but densities close to tree rows were still significantly greater ($p < 0.05$) than those from a comparable conventionally cropped corn field. Differences in earthworm numbers between spring 1997 and spring 1998 likely resulted from differences in temperature and precipitation between the two sampling periods. The average monthly temperature in the spring of 1998 was almost double than that in the spring of 1997 (15.6 °C versus 7.9 °C); in addition, total precipitation was 34.2 mm in 1998 and 82.2 mm in 1997. It is likely that these differences contributed greatly to the lower earthworm numbers in the spring of 1998, due to the environmental sensitivities of earthworms (Edwards and Bohlen 1997; Lee 1985).

The increased nutrient deposition due to stemflow, throughfall, and litterfall under trees (Rhoades 1997; Zhang 1999) as compared to under corn may be responsible for the higher numbers and biomass of earthworms observed in this study. These organic matter and nutrient additions can significantly influence earthworm populations in the soil (Zwart et al. 1994; Willems et al. 1996). Microclimatic differences attributed to the presence of trees in the intercropped situation may also have been responsible for greater earthworm numbers and biomass, even though further study is required to confirm this. We have observed distinct earthworm dispersal patterns within our tree-based intercropping system that might be linked to the microclimate gradient between tree rows and the middle of the crop alley (Price 1999; Williams and Gordon 1995).

Soil micro and macro faunal diversity and their abundance in biomass production ecosystems can be used as sustainability indicators. The threshold values need to be developed based on soil and environmental conditions.

1.2.2 Soil Carbon (C) and Nitrogen (N)

Given the current interest on climate change mitigation strategies, enhancement of C sequestration in terrestrial ecosystems has been emphasized and has also been promoted as a potential mitigation strategy. In this context, agroforestry-based biomass production systems can play a major role toward sequestering atmospheric CO_2. However, as the aboveground biomass is utilized for energy production, C tied up in the aboveground biomass is lost during energy utilization either through combustion or biochemical and thermochemical processes. Therefore, in these production systems, emphasis should be given to belowground C sequestration in roots and also in soils.

In relation to soil N, biomass production systems have shown an optimal use of soil N and return of this N to the soil via litterfall, stemflow, and throughfall (Cardinael et al. 2012; Zhang 1999; Thevathasan et al. 2004; Thevathasan and Gordon 2004).

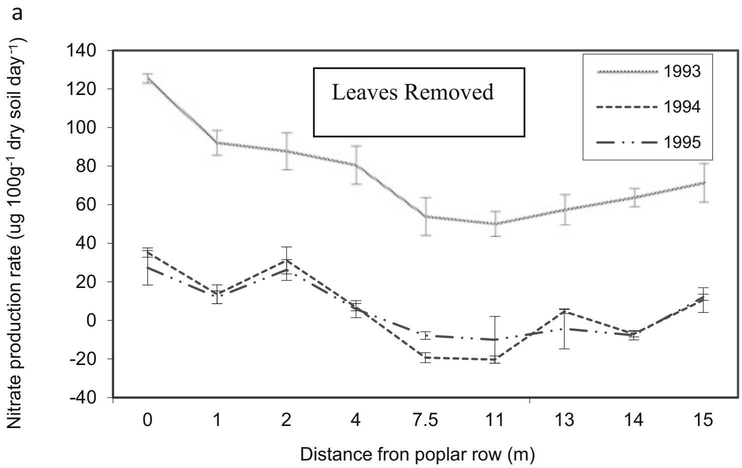
The effects of litterfall distribution of poplar (hybrid clone DN 177; *Populus deltoides* × *Populus nigra* 177) on soil nitrogen (N) transformations and soil organic carbon (SOC) were studied from 1993 to 1995 and then again in 2002. The associated crop was barley (*Hordeum vulgare*); the poplar trees were 6 years old in 1993 (15 years in 2002). Even though the above experiment was conducted having barley as an annual crop in the alleys, similar results associated with litterfall distribution and its positive influence on soil C and N dynamics in the intercropped biomass crop willow have also been reported by Clinch et al. (2009) and Cardinael et al. (2012).

The results presented here and discussed are associated with the University of Guelph Agroforestry Research Site in southern Ontario, Canada. In field experiment 1 (Fig. 1.5a), poplar leaves were removed after leaf senescence in 1993 and 1994; in experiment 2, leaves were not removed (Fig. 1.5b).

Poplar litterfall distribution on the ground showed a distinct pattern, with almost 80% of the leaves falling within 2.5 m from the tree row (Table 1.6).

Differing rates of poplar leaf biomass input across the alleyways created distinct regions with respect to the accumulation of soil nitrogen and carbon. Based on the abundance of these resource pools, the intercropped alley can be divided into three zones: the area close to the poplar tree row (0 to 2.5 m on either side of the tree row, zone 1), the middle of the crop alley (2.5 to 8.0 m from the tree row, zone 2), and the area furthest away from the tree row (8.0 to 15.0 m, zone 3) [Note: The experiments were designed with the poplar tree row as the middle row; the two adjacent tree rows did not have any poplar trees, but did have small white ash and black walnut trees. These trees were less than 2 m high at age 6 and did not contribute any sizable quantity of leaf biomass (Thevathasan and Gordon 1997)]. Observed mean soil nitrate production in the aforementioned zones during June to August 1993 was 73.1, 41.0, and 34.0 μg 100 g^{-1} dry soil day^{-1}, respectively (Fig. 1.5a, b). The higher nitrate production rates in 1993 were due to the presence of 1992 fall-shed poplar leaves. In 1995, as a result of the removal of poplar leaves from the field for two consecutive years (1993 and 1994), nitrate production rates decreased to 17.6, −2.8, and − 1.7 μg 100 g^{-1} dry soil day^{-1} in the same zones, respectively (Fig. 1.5a). In experiment 2 (June to August 1995, leaves not removed), however, mean nitrate production in the same zones was 109.4, 15.4, and 5.7 μg 100 g^{-1} dry soil day^{-1}, respectively (Fig. 1.5b). What this implies is that in tree-based biomass production systems, as there will be leaf litter or leaf biomass from both mature high-value trees and intercropped biomass crops, available soil N can be considered as a sustainability indicator to assess the soil fertility. In addition, the soil N comes from the organic source, and it is slowly released as the leaves decompose, and therefore it also prevents nitrate-N leaching into our water sources.

There is much information available on tropical hedgerow intercropping systems where nutrient release occurs through the mineralization of recently added hedgerow pruning and root decay (Rao et al. 1998). In these systems, considerable labor input is required to bring about this desirable complementary interaction. In the temperate region, and especially with tree species that have the potential to produce high leaf biomass (e.g., hybrid poplar), no special effort is made for soil incorporation of leaf biomass. Nitrogen release from annual poplar litterfall at the University of Guelph



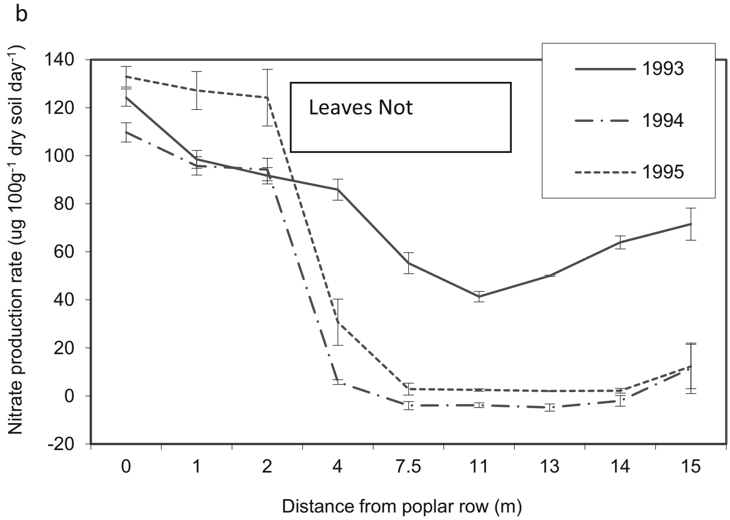


Fig. 1.5 Effects of removing or retaining poplar tree leaf on soil N mineralization near the tree row (up to 2.5 m horizontal distance) in the tree-intercropping study during 1993–1995 in southern Ontario, Canada; (**a**) leaves removed; (**b**) leaves not removed
Source: Thevathasan (1998)

Table 1.6 Poplar litterfall distribution in a poplar-barley intercropping system during the 1993 and 1994 growing seasons when trees were 6 and 7 years old, respectively, Guelph, Ontario, Canada (From Thevathasan and Gordon 1997)

Litterfall biomass (Mg ha^{-1} y^{-1})		
Distance from the poplar tree row (m)	1993	1994
0–2.5	2.67 ± 0.04	2.76 ± 0.14
2.5–6.0	0.52 ± 0.05	0.61 ± 0.06

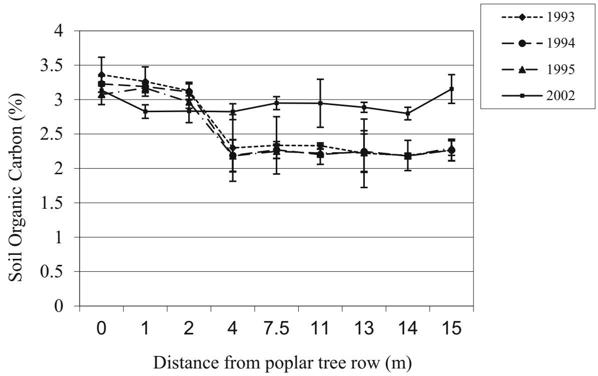


Fig. 1.6 Soil organic carbon content at various distances from poplar tree row in 1993, 1994, 1995, and 2002, when the trees were 6, 7, 8, and 15 years old, in the tree-intercropping experiment in southern Ontario, Canada. Error bars that overlap indicate that associated values are not significant at $p < 0.05$. Source: Thevathasan and Gordon (1997)

Agroforestry Research Station has been estimated to be equivalent to 7 kg N ha^{-1} y $-$ ^{1}. This implies that rates of inorganic N fertilizer input in the poplar-based biomass alleys could be reduced by this amount, which, in turn, can directly reduce input costs.

Soil organic carbon did not change significantly ($p < 0.05$) in the three indicated zones from 1993 to 1995 with recorded SOC zone means of 3.25, 2.32, and 2.50% respectively (Fig. 1.6). This was to be expected as only 15 to 35% of added organic residue is actually incorporated into the permanent organic pool (humus) (Brady and Weil 2002).

The high rate of poplar leaf biomass addition (1 Mg C ha^{-1} y^{-1}) over a total period of 8 years resulted in an increase of SOC of approximately 1% close to the tree row, and this effect extended into the alley for up to approximately 4 m (Fig. 1.6). This is about a 35% relative increase (percentage difference between 3.25 and the mean of 2.32 and 2.50) in SOC close to the tree rows over the given period of time and reflects leaf biomass inputs in the early 1990s, when trees were small and the major portion of litterfall was distributed close to the tree row (2 to 3 m) (Table 1.6). By 2002, poplar trees were 14 m tall, and leaf biomass was evenly distributed across the crop alley up to distances of 15 m. This resulted in a slow but inexorable increase in soil C in the middle of the crop alley, as illustrated in Fig. 1.6.

In another agroforestry-based biomass production study using willow as the biomass crop in the alleys on the same site established in 2006, baseline soil C levels were quantified in order to assess long-term soil C sequestration potentials. As a result of leaf and fine root turnover, soil organic C values are being enhanced over time from 1.31% in 2006 to 2.65% in 2012 (Fig. 1.7) in the agroforestry system. In this system, willow crop was grown in the alleys between widely spaced mature walnut trees. In the control field, willow crop was grown as a sole crop in the absence of mature walnut trees. As there are mature trees grown in the widely spaced tree rows, agroforestry-based biomass production systems can therefore enhance aboveground C sequestration and contribute positively toward system-level C sequestration. However, in a sole-cropped willow biomass system, as the aboveground biomass is periodically harvested, only soil C sequestration can contribute toward system-level C sequestration. Therefore, agroforestry-based biomass production

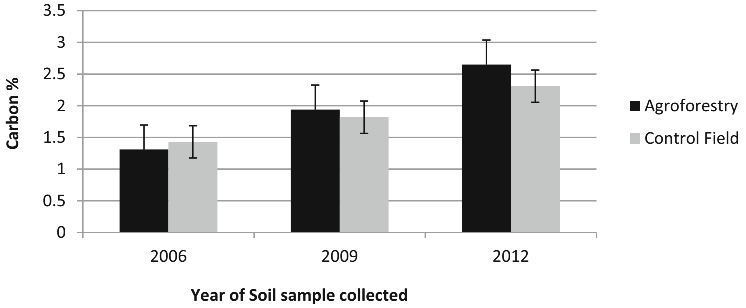


Fig. 1.7 Soil organic carbon sequestration potential in an agroforestry and sole-cropped-based willow biomass production system in Guelph, Ontario, Canada

systems have the added advantage toward enhancing C sequestration at the system level.

1.3 System-Level Carbon Sequestration Potential in Agroforestry Biomass Systems

A recent study was conducted by Wotherspoon (2014) on the University of Guelph Agroforestry Research Station to assess the system-level C sequestration potential of five different tree species, namely, poplar, walnut, Norway spruce, oak, and white cedar, grown for the last 25 years in a tree-based intercropping system. Even though the crop grown in the alleys was soybean (*Glycine max*), it did not contribute to any C sequestration. In this context, C sequestered by mature trees in the last 25 years at the same site can therefore be accounted for system-level C sequestration by these respective tree species if they were integrated into a tree-based biomass production system in southern Ontario.

System-level C sequestration potentials of the above indicated tree species are presented in Table 1.7.

Above- and belowground tree C content, soil organic C, soil respiration, litterfall, and litter decomposition were quantified for each tree species in each system. Total C pools for poplar, cedar, oak, walnut, spruce, and soybean sole cropping system were 113.4, 99.4, 99.2, 91.5, 91.3, and 71.1 Mg C ha^{-1}, respectively, at a tree density of 111 trees ha^{-1}, including mean tree C content and soil organic C stocks. Net C flux for poplar, spruce, oak, walnut, cedar, and soybean sole crop were + 2.1, +1.6, +0.8, +1.8, +1.4, and − 1.2 Mg C ha^{-1} y^{-1}, respectively. Results presented suggest greater atmospheric CO_2 sequestration potential for all five tree species when compared to a conventional agricultural system.

From this study and based on the results presented above, it can be concluded that quantitative values can be generated for system-level C sequestration in agroforestry-based biomass production systems and be also used as system-level sustainability indicators.

Table 1.7 Carbon sequestration (Mg C ha^{-1} y^{-1}) potentials of five tree species commonly grown in tree-based intercropping systems in comparison to conventional agricultural systems in southern Ontario, Canada (From Wotherspoon 2014)

Inputs	Poplar	Oak	Walnut	Spruce	Cedar	Soybean monocrop
Aboveground tree C assimilation	0.83	0.46	0.48	0.38	0.53	
Belowground tree C assimilation	0.23	0.16	0.11	0.14	0.12	
Litterfall C inputs	1.63	1.07	1.50	1.49	0.68	
Fine root turnover	0.82	0.54	0.75	0.45	0.20	
Above and belowground crop C input	1.22	1.22	1.22	1.22	1.22	1.40
Outputs (via decomposition)						
Litterfall C outputs	1.04	0.54	1.44	0.63	0.26	0
Root output	0.52	0.27	0.72	0.19	0.08	1.31
Crop C outputs	1.00	1.00	1.00	1.00	1.00	1.19
C leachate	0.05	0.05	0.05	0.04	0.04	0.05
Net						
Net C balance	+2.12	+1.58	0.84	+1.81	+1.36	−1.15

1.3.1 Water Quality

In order to test the "safety-net hypothesis" theory—double filtration by crop roots and tree roots, a mini-watershed study was conducted in the agroforestry research site in 2005 and 2006. Results from this study indicated that tree roots have the capacity to filter leached nutrients, especially nitrate-N and to some extent *E. coli* NAR. This filtration of nutrients and microorganisms by mature trees in an agroforestry system should have positive effects on the water quality. When woody biomass is grown in the alleys, the filtration aspect may be amplified as perennial roots can absorb all residual soil nitrogen right through the growing season and into the fall season. Agricultural crops have limitation as they get harvested late in the summer or at the end of the growing season.

Tile drain effluent from two adjacent agricultural systems (a mixed tree intercrop and a monocrop) was collected from April to November during 2005 and 2006 from a paired mini-watershed area of 17,200 m^2. An area of 1100 m^2 (6.4%) in each system was subject to application of a mixture of water and a biotracer *E. coli* NAR, a naturally occurring strain that is resistant to nalidixic acid and has been shown to be safe for introduction into the environment. The effluent was analyzed for concentrations of the biotracer and NO_3-N. The premise of this study is to determine if the safety-net hypothesis is valid in a temperate intercropping system. This hypothesis states that the incorporation of trees into agricultural systems will allow for a more efficient use of resources, since the rooting system of the trees captures nutrients that are not captured by the crop component of the system.

Table 1.8 Nitrate-N leaching values across all sampling dates in 2005 (From Dougherty et al. 2009)

Date	Mean daily loss via leaching (kg ha^{-1})		p-value	Total loss via leaching (kg)	
	Monocrop	Intercrop		Monocrop	Intercrop
April 7– May 21	1.05a ± 0.016	0.93b ± 0.013	< 0.001	44.46	43.73
Aug 18–Sept 30	0.09a ± 0.011	0.02b ± 0.003	< 0.001	0.71	0.19
Nov. 8–31	0.87a ± 0.058	0.76b ± 0.06	< 0.001	12.20	10.81
Total				57.37	54.74

Table 1.9 Nitrate-N leaching values across all sampling dates in 2006 (From Dougherty et al. 2009)

Date	Mean daily loss via leaching (kg ha^{-1})		p-value	Total loss via leaching (kg)	
	Monocrop	Intercrop		Monocrop	Intercrop
Mar 21–Apr 30	1.09a ± 0.023	0.59b ± 0.017	< 0.001	44.33	24.67
May 1–June 12	1.16a ± 0.016	0.58b ± 0.011	< 0.001	44.52	22.20
July 4–Aug. 7	0.76a ± 0.034	0.54b ± 0.027	< 0.001	14.66	9.86
Sept. 28–Nov. 21	1.11a ± 0.021	0.58b ± 0.021	< 0.001	61.16	31.86
Total				164.67	88.59

The quantities of nitrate in the leachate were similar in 2005, 57.37 and 54.74 kg ha^{-1}, leached from the monocrop and intercrop sites, respectively (Table 1.8). However, in 2006, nitrate levels were significantly higher ($p < 0.05$) in the monocrop effluent, 164.67 kg ha^{-1}, compared to that of the intercrop, 88.59 kg ha^{-1} (Table 1.9). It was, therefore, concluded few significant differences were found in *E. coli* NAR outputs during both years; however, there is an indication that intercropping systems and perhaps trees in general have a potential mitigating effect on *E. coli* movement to the groundwater. For the same number of samples collected, the total colony-forming units (CFUs) found in the monocrop and intercrop effluents, respectively, were 4040 and 3558 in 2005. In 2006, 34,025 and 28,401 were enumerated from the monocrop and intercrop treatments, respectively, given the same number of samples.

In other studies, it has been reported that properly designed and well-managed plantations reduce sediment and nutrient inputs to waterways (Perttu 1995; Updegraff et al. 2004) and may become a tool for improvement of water quality (Londo 2002). They can be used as vegetation filters for sources of contamination such as urban wastewater, food industry aqueous waste, landfill leachate, sewage sludge, wood ash, and log yard runoff (Sims and Riddell-Black 1998; Dimitriou and Aronsson 2005) or as tools for the phytoremediation of sites contaminated by heavy metals (Perttu 1995) and radioactive elements (Vandenhove et al. 2002). All these remedial processes can have a direct positive influence on the water quality.

1.4 Greenhouse Gas Reduction Potentials

Not many studies have been conducted in relation to greenhouse gas (GHG) emissions from agroforestry systems. However, due to enhanced nutrient use efficiency via nutrient cycling, it is believed that tree-based agroforestry systems have the potential to reduce GHG emissions. From numerous research studies conducted at the Agroforestry Research Site at the University of Guelph, nitrous oxide emission reduction potential was calculated as described in Table 1.10.

In order to verify the above calculation, Evers (2009) conducted an experiment at the same research site, and he found that a tree-based intercropping (TBI) system in southern Ontario lowered N_2O emissions by 1.2 kg ha^{-1} y^{-1} compared to a conventional monoculture. This difference was not significant statistically but over time could contribute significantly toward climate change mitigation (Table 1.11).

1.4.1 Nutrient Cycling

The aspect of nutrient cycling in agroforestry-based biomass systems has not been researched much. However, as these systems would comprise of mature trees in the

Table 1.10 The potential for annual N_2O-N reduction, 8 years after establishment of trees, based on hypothetical N cycling budget developed for a fast-growing hybrid poplar-based intercropping system, Guelph, Ontario, Canada (From Thevathasan and Gordon 2004)

Causes of N_2O reduction	N fertilizer saved (kg ha^{-1})	N_2O emission reduction (N_2O-N kg ha^{-1})
10% less land area	8[a]	0.1[b]
N cycling in tree-based intercropping	7	0.09[c]
Reduction in N leaching	20	0.5[d]
Total N_2O reduction potential		0.69

[a]Maize, bean, wheat rotation, average annual N fertilizer application = 80 kg ha^{-1}
[b]$8 \times 0.0125 = 0.1$ (1.25% of the applied fertilizer N is lost as N_2O)
[c]$7 \times 0.0125 = 0.09$
[d]$20 \times 0.025 = 0.5$ (2.5% of the leached N is lost as N_2O)

Table 1.11 Mean N_2O flux (g ha^{-1} day^{-1}) in the monocropped and agroforestry fields during the summer 2007, fall 2007/winter 2008, spring 2008, and summer 2008 seasons (From Evers et al. 2010)

	N_2O flux (g ha^{-1} day^{-1})			
Field	Summer 2007	Fall 2007/winter 2008	Spring 2008	Summer 2008
Monoculture	4.5[†]	13.1	9.3	15.7
Agroforestry	−2.8	6.8	9.3	16.7
Se[a]	5.5	15.1	5.1	2.6
p-value	0.4116	0.7699	0.9972	0.8057

[a]*Se* standard error

Table 1.12 Annual nutrient inputs by litterfall, net throughfall, and net stemflow at the University of Guelph Agroforestry Research Station, Guelph, Ontario, Canada (From Thevathasan et al. 2004)

	Total N	NO_3-N	NH_4-N	P	K	Ca	Mg
	kg ha^{-1} y^{-1}						
Black walnut							
Litterfall	1.74a			0.15a	0.50a	3.08a	0.77a
Net throughfall		0.06a	0.09a	0.175a	2.99a	2.21a	0.92a
Net stemflow		0.01a	0.004a	0.32a	0.08a	0.06a	0.02a
Total		0.07	0.10	0.63	3.57	5.35	1.71
Red oak							
Litterfall	4.6b			0.35a,c	1.87b	11.09b	3.29b
Net throughfall		0.24b	0.34b	0.14a	1.29a	1.39a	0.42a
Net stemflow		0.01a	0.01a	0.13a	0.08a	0.05a	0.01a
Total		0.25	0.35	0.62	3.24	12.53	3.73
Silver maple							
Litterfall	15.22c			0.99b	3.13c	15.51b	2.50b
Net throughfall		2.73c	3.05c	0.12a	7.67b	8.93b	2.77b
Net stemflow		0.05b	1.20b	4.10b	0.24b	0.12b	0.04b
Total		2.78	4.25	5.21	11.04	24.56	5.31
Hybrid poplar							
Litterfall	10.99d			1.06b	5.49d	28.51c	7.27c
Net throughfall		1.75d	0.73b	0.38b	15.44c	8.99b	2.71b
Net stemflow		0.03b	0.01a	3.56b	0.29b	0.11b	0.05b
Total		1.78	0.74	4.99	21.22	37.61	10.03
White ash							
Litterfall	4.86b			0.51c	1.84b	13.38b	2.37b
Net throughfall		0.32b	0.10a	0.048c	1.62a	2.02a	0.62a
Net stemflow		0.01a	0.002a	0.24a	0.08a	0.04a	0.01a
Total		0.33	0.11	0.79	3.54	15.44	3.01

By parameters and nutrient, values followed by the same letter across species are not significantly different (LSD, $p < 0.05$)

tree rows, nutrient cycling studies from tree-based intercropping systems can be looked at to understand the nutrient cycling dynamics in potential biomass production systems.

Trees may intercept airborne particles by trapping them on leaf surfaces. These chemicals, along with chemical elements naturally occurring in tree components, especially in leaves, are then washed off into the soil by rainfall events. This process creates a sphere of influence beneath the tree canopy whereby soil nutrient levels may be slightly higher than in cropping systems that do not possess tree canopies. A study at the University of Guelph examined nutrient additions through two important hydrologic pathways: throughfall (rainwater falling through tree canopies) and stemflow (rainwater falling down the branches and stems). The annual nutrient inputs from tree leaf litterfall, net throughfall, and net stemflow for five intercropped tree species are presented in Table 1.12 (Thevathasan et al. 2004).

Hybrid poplar and silver maple contributed the most N through these pathways, especially through leaf litterfall. The movement of nutrients through the hydrologic pathways varied depending on tree species and on the nutrient itself. For example, a higher percentage of potassium (K) was carried in the net throughfall than in the stemflow for all of the species observed. The nutrient contributions (available N, Ca, K, and P) through these hydrologic pathways and through leaf litter can enhance soil structure by increasing organic matter (OM) content and by producing a nutrient-rich substrate for microbial processes. This, in conjunction with the well-known ability of trees to modify microclimate (e.g., reduced wind speed, low evapotranspiration demands; Brandle et al. 2000) likely contributed toward increased winter wheat yields close to the intercropped tree rows. Winter wheat grain yields in the intercropping system and in a monocropping system were 2450.3 kg ha^{-1} and 2244.4 kg ha^{-1}, respectively. This translates to an 8.4% wheat grain yield increase in the intercropping system compared to the monocropping system. Therefore, these nutrient additions can also positively influence biomass production in the alleys between tree rows comprising of these respective tree species. The ability of these systems to efficiently cycle nutrients will require less external inputs in terms of inorganic fertilizer applications, thereby enhancing the ecosystem health.

1.5 Biomass Production and Carbon Sequestration in Riparian Buffer Systems and Associated Environmental Benefits

Among the temperate agroforestry systems, riparian buffer plantings have the greatest potential to produce biomass while enhancing biodiversity, environmental, and ecosystem services. The reason is that the tree density in riparian plantings can be increased as there are no associated annual crops grown under these plantings. Also, as they are gown in the terrestrial-aquatic interface of both lakes and streams, competition for moisture is seldom a limiting factor. They also exert a disproportionate regulatory influence over many important ecological processes at many scales. In agricultural landscapes, preservation of biodiversity, flood erosion control, and their ability to remove nutrients from agricultural runoff are among the many important attributes of riparian areas. However, it is important to realize that the verification and enhanced understanding of these attributes can only be realized from the application of long-term ecological studies in riparian zones. In this context, and also to address biomass production potentials under riparian management, several research studies were undertaken by the University of Guelph researchers on a degraded stream, Washington Creek, in the town of Washington, Ontario. These studies were conducted at different time spans: during the establishment phase (1985 to 1990) and in mature stands (2006 to 2007).

Washington Creek is a 9-km-long spring-fed first-order stream located in Oxford County, an agriculturally dominated landscape in southern Ontario. The stream enters the Nith River (within the Grand River watershed) south of Plattsville (43°18’N, 80°33’W) and is typical of agriculturally degraded streams in the region, being surrounded by cropped fields and pasture and possessing a general lack of riparian vegetation and numerous areas with a high degree of streambank erosion where animals (e.g., cattle) have access to sections of the water. The physiography of Oxford County is characterized by sandy hills and kames. Soil parent material of the drainage basin is glacial till (Pleistocene) overlying limestone bedrock (Silurian). Soils of the Washington Creek study site are classified as silt loams (pH = 7.1; CaCO3 = 6.2%) with an organic matter and N content of 7.1% and 0.4%, respectively. Please see Fig. 1.8 a, b and c; photos were taken during different stages of riparian vegetation development.

Beginning in 1985, the streambank along a 1.6 km section of Washington Creek was planted with a variety of alder [*Alnus incana* subsp. Rugosa (Du Roi) R.T. Clausen., *Alnus glutinosa* Gaertn., and *Alnus rubra* Bong] and hybrid poplar (*Populus* × *canadensis* Moench) trees. All trees were planted in four rows with 3 × 3 m spacing. Biomass derived from the thinning study from the above indicated plantings ranged between 4 and 5 odt (oven dry ton) ha^{-1} y^{-1} (Gordon et al. 1992; Simpson et al. 1993).

During the same time period (1985 to 1990), the University of Guelph also initiated two other satellite riparian buffer plantings in the Grand Valley watershed, northwest of Toronto, Ontario, and in Cambridge, Ontario. In the former site, hybrid willow (*Salix* sp.), hybrid poplar, silver maple, and green ash (*Fraxinus pennsylvanica*) were planted at a spacing of 0.5 m × 0.5 m to result in a tree density of 40,000 trees ha^{-1}. This high density was used to maintain these sites as short-rotation systems. The willow trees gave the highest biomass yields due to their inherent capacity to coppice and produce multiple stems from a single stool. It should be noted that even about quarter century ago, willow was identified as a suitable biomass crop as being recommended by various organizations in Canada and in Europe. The biomass results derived from these experiments are presented in Tables 1.13 and 1.14.

Carbon sequestration potential by riparian plantings was assessed during 2006 and 2007 in the mature stands of poplar at the Washington Creek site. Three 22-year-old poplar trees were sampled in the current study. The total mean C sequestered in the permanent woody components of the fast-growing hybrid poplar was 279 Mg ha^{-1} (1111 trees per hectare, at 3 m × 3 m row spacing, Table 1.15). In addition, the C contribution to soil from leaf litter and fine root turnover for the last 22 years totals approximately 45 Mg ha^{-1}. The total contribution in terms of carbon sequestration over the last 22 years at this experimental site (Washington Creek) is therefore approximately 324 Mg C ha^{-1}. Theoretically, this also implies that this system has immobilized 1189.1 (324 × 3.67) Mg of CO_2 ha^{-1} in the last 22 years. However, 67.5% of the C added via leaf litter and fine roots will be released back into the atmosphere through microbial decomposition (Gordon and Thevathasan 2005) [45 Mg ha^{-1} × (1–0.675) = 14.63 Mg ha^{-1} in soil], and therefore, the net annual sequestration potential from the trees alone is [279 (permanent woody component, excluding leaves and fine roots) + 14.63 (in the soil after microbial respiration)] = 293.63 (total in the wood and in the soil)/22 (years) = 13.35 Mg C ha^{-1} y^{-1} or approximately 49 Mg of CO_2 ha^{-1} y^{-1}.

Fig. 1.8 Washington Creek (**a**) as it was in 1985, prior to rehabilitation; (**b**) after thinning for biomass data in 1989; and (**c**) in 1995

1.5.1 What Does this Mean to the Landowner?

Let us consider a hypothetical scenario. If a landowner has 1 km or 1000 linear meters of creek flowing through his/her farm and if he/she plants hybrid poplar on a 10 m buffer at 3 m × 3 m spacing, he or she will have 1111 trees per hectare

Table 1.13 Biomass accumulation (odt ha^{-1}) from three potential biomass species for riparian plantings after one growing season in the Grand Valley watershed, Toronto, Ontario, Canada (adapted from Simpson et al. 1993)

Species	Biomass (odt ha^{-1})
Willow sp	15.25a
Silver maple	12.21ab
Poplar sp.	9.73b

Means within column followed by the same letter are not significantly different ($p < 0.05$)

Table 1.14 Biomass productivity of willow clones planted in Cambridge, Ontario, Canada (Adapted from Simpson et al. 1993)

Willow clone	Biomass (odt ha^{-1})
301	6.63
185	6.59
652	5.5
259	5.37
594	4.32
184	3.43
557	2.51

Table 1.15 Carbon content of individual tree components for hybrid poplar growing in the riparian system. The total C sequestered per tree in 22 years [in permanent tree components, excluding leaves] is [273.42–22.4 = 251 ± 16.3 (kg)]

Tree components	Biomass dry weight (kg)	Carbon concentration (%)	Carbon content (kg)
Leaves	52.1 ± 7.5	43	22.4 ± 3.5
Twigs	28.0 ± 4.1	44	12.32 ± 2.3
Small branches (<7 cm dm.)	65 ± 11.3	45	29.25 ± 6.2
Large branches (>7 cm dm.)	125.0 ± 31.2	45	56.25 ± 17.3
Trunk	270.4 ± 68.8	40	108.2 ± 33.5
Total aboveground biomass	540.5 ± 43.6	–	228.42 ± 17.2
Roots	104.5 ± 10.9	43	45.0 ± 4.7
Total	645		273.42

(10,000 m^2). This planting will sequester, on an annual basis, 13.35 Mg C ha^{-1} as calculated above from this research project.

One liter of gasoline consists of 0.65 kg of C, and 1 liter of diesel fuel consists of 0.74 kg of C. Based on these numbers and findings from this research project, Table 1.16 describes the amounts of fossil fuel a landowner could use and still be carbon neutral.

Table 1.16 A guide to landowners to become carbon neutral or as to how they can reduce their carbon "footprint"

	Linear creek length (1 km or 1000 m)	Maximum usage of fossil fuel in liters per year[a] Gasoline (0.65 kg C L^{-1})	Maximum usage of fossil fuel in liters per year[a] Diesel (0.74 kg C L^{-1})
C sequestration potentials in a 10 m buffer planted with hybrid poplar at 3 m × 3 m spacing (Mg ha^{-1} y^{-1})	13.35	20,538	18,041
C sequestration potentials in a 15 m buffer planted with hybrid poplar at 3 m × 3 m spacing (Mg 1.5 ha^{-1} y^{-1})	20.03	30,815	27,068
C sequestration potentials in a 20 m buffer planted with hybrid poplar at 3 m × 3 m spacing (Mg 2 ha^{-1} y^{-1})	26.70	41,077	36,081
C sequestration potentials in a 25 m buffer planted with hybrid poplar at 3 m × 3 m spacing (Mg 2.5 ha^{-1} y^{-1})	33.38	51,354	45,108
C sequestration potentials in a 30 m buffer planted with hybrid poplar at 3 m × 3 m spacing (Mg 3 ha^{-1} y^{-1})	40.10	61,692	54,189

[a]Note: Maximum fuel consumption numbers reported in Table 1.16 does not include greenhouse (GHG) emissions from fertilizer use or pesticide use. When these factors are taken into consideration and also based on the acreage farmed, maximum fuel consumption numbers will be lower than that reported in Table 1.16. The whole purpose of Table 1.16 is just to provide an idea as to how to reduce the carbon "footprint" on southern Ontario farms by adopting agroforestry-based land-use systems such as riparian buffer systems

1.5.2 Biodiversity

At the Washington creek riparian research site, several biodiversity assessments were conducted during the first 10 years after establishment (1985 to 1995) and also during 2006 to 2007 in the mature stand.

However, during 2006 and 2007, verification of processes was conducted on the four land-use systems that interact with the stream (Fig. 1.9): (1) a natural forested region (NF), containing tree species common to southern Ontario (e.g., *Acer*, *Betula*, *Fraxinus*, etc.), (2) a pasture area in which cattle have traditionally had access to the stream for a source of drinking water (LV), (3) a cropped area supporting a standard soybean-corn rotation (AP), and (4) a "rehabilitated" section (RA) composed of planted trees now approximately 22 years of age. Each land use constitutes between 0.5 and 1.6 km of linear streambank and exists in the order described above, with land use no. 1 being the furthest upstream and land use 4 being the furthest downstream. (Acronyms: *NF*, natural forest; *LV*, livestock; *AP*, agricultural and pasture field; *RA*, rehabilitated area).

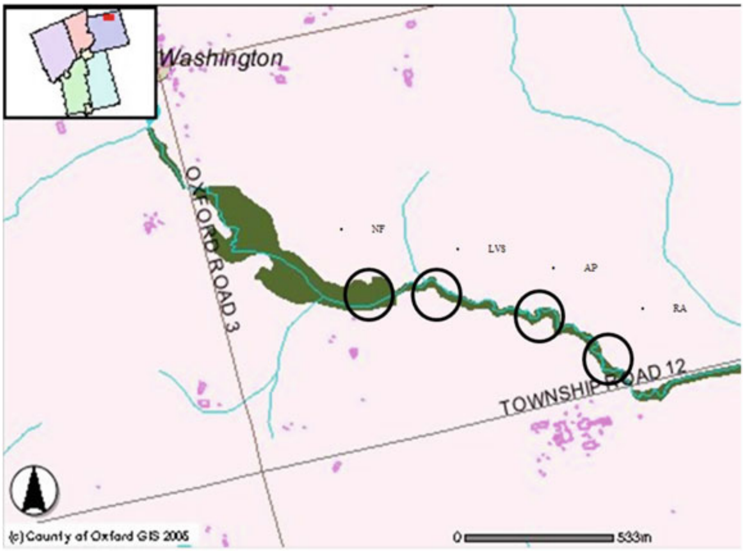


Fig. 1.9 NF, natural forest; LV, livestock; AP, agricultural and pasture field; and RA, rehabilitated area

A comparison of verified attributes derived from these distinct land-use systems should demonstrate the importance of riparian zone rehabilitation or riparian zone best management practices (BMPs). A concerted effort is made to present the verified results from this project within the context of ecological, economic, and social impacts, with the goal of developing a stronger insight into how the various competing values of riparian areas in agricultural landscapes might be more effectively balanced. The parameters that were assessed during 2006 and 2007, in addition to biodiversity, therefore can be considered as potential sustainability indicators for riparian-based biomass production systems.

Results are presented in the order of establishment time period assessments (1990) followed by assessments made in the mature stands (2006/2007). However, it should be noted that the 2006/2007 survey only consisted of measuring plant and tree diversity.

1.5.2.1 Bird Diversity

In the 1990 study, the study site was partitioned into four separate areas, three afforested sections divided on the basis of width and plant species composition and one upstream control area (site D) characterized by grasses and little other riparian vegetation. Of the three afforested sections, site A was located along a channelized section of the stream, with one row of poplar or alder trees on each bank. Site B was a wider area, approximately 50 m in width on average, and characterized by a predominance of trees, with an understory of weeds and grasses. Site C averaged 100 m in width and also consisted of abundant natural understory vegetation and trees. Two or four 600 m^2 sampling sites were randomly assigned to each

Table 1.17 Sample area descriptions and bird species diversity of the 1990 Washington Creek bird population study

Area	Riparian zone identifier	Species diversity
A	1 row of 5-year-old poplar, alder, uniform composition	9.5
B	50 m width, older trees with alder, poplar, walnut	11
C	100 m width, older trees with alder, poplar, walnut	11.75
D	Control – Grazing area, no riparian shrubs or trees	10.5

Table 1.18 Total number of species observed nesting and foraging at four different habitat types at Washington Creek with associated Shannon index of diversity (H'i)

	Nesting	Foraging	H'i
Site A (channel)	3	10	0.4771
Site B (park)	5	13	0.6923
Site C (natural)	8	17	0.8767
Site D (control)	3	10	0.468

area, and the bird species present in each site over a 4-day period in June were noted (Table 1.17).

Division of the study area by plant communities and buffer width resulted in four distinct areas. Bird species diversity, defined as average number of species over the sampling period, ranged from 11.75 in Area C to 9.5 in Area A (Table 1.17); however, species diversity was not significantly different between any of the sites ($p < 0.05$). Of the 24 bird species sighted in the entire forested region within the 4 days of sampling, 24% were missing from Area A, the single row of poplars. Only five bird species were found to nest in the channelized area (Area A): these were red-winged blackbird (*Agelaius phoeniceus*), song sparrow (*Melospiza melodia*), American goldfinch (*Carduelis tristis*), northern oriole (*Icterus galbula*), and yellow warbler (*Dendroica petechia*). The densities of these nests were also noted to be lower than in either of Area B or C. No birds were observed nesting in the control area (Area D).

As riparian habitat (i.e., buffer strip) size increased from site A through C, there was an apparent corresponding increase in bird species nesting and foraging (Table 1.18). Diversity in the naturalized area (site C) was greater than in both the control area (site D) and the narrow buffer strip of the channelized section (site A), but was not significantly different from the park area (site B; $p < 0.05$).

1.5.2.2 Plant Diversity

Many of the benefits associated with riparian buffer zones are a direct result of the type and quantity of vegetation growing in the area. The advantages of maintaining a diverse vegetative community include improved water quality, sedimentation and erosion control, and enhanced fish and wildlife habitats. Vegetation can also act as a physical barrier to runoff, from agricultural land, increasing the potential for infiltration of water and filtration of soil and debris before entering the stream.

It is well known that plant diversity can be highest in areas with moderate levels of disturbance, while dense forests tend to have low diversity of understory species. It is also known that rehabilitated agricultural land often continues to be populated by the "weedy" species that thrive on disturbed land, sometimes long after rehabilitation activities have taken place. However, it has been found in some cases that planting trees to rehabilitate an area can result in the return of native understory plants relatively quickly due to the habitat conditions created by the trees (habitat not just for the plants themselves but for birds and other animals that may help to disperse native plant propagules to newly reforested areas). The purpose of this study was to compare plant diversity and community composition in a rehabilitated riparian forest and a nearby natural riparian forest at Washington Creek (Figs. 1.10 and 1.11), to investigate the extent to which the vegetation in the rehabilitated area is approaching a natural forest condition.

We found 48 species in the rehabilitated area and 25 in the natural forest area (Fig. 1.9). The results from the "jackknife" procedure confirmed that the rehabilitated area was more diverse than the natural forest, with estimates of 64 and 49 species, respectively. Results reported hereafter will be based on the species richness estimates from real sampling. Per-quadrat species richness in the rehabilitated area was 6.9 species, while in the natural forest, this value was 3.3 species, indicating that the rehabilitated area was more diverse than in the natural forest.

The understory in the rehabilitated area was dominated by pioneer species ("weedy" species characteristic of disturbed areas), such as the mustards (e.g., *Alliaria officinalis*), burdocks (*Arctium* spp.), and pigweeds (*Amaranthus* spp.). The natural forest was dominated by forest species (e.g., woodland strawberry (*Fragaria vesca*)) and intermediate species (those characteristic of both closed forests and disturbed areas) (Figs. 1.10 and 1.11).

It is likely that the more open tree canopy, pre-existing seedbank, and proximity to actively tilled crop fields are influencing the understory plant community in the

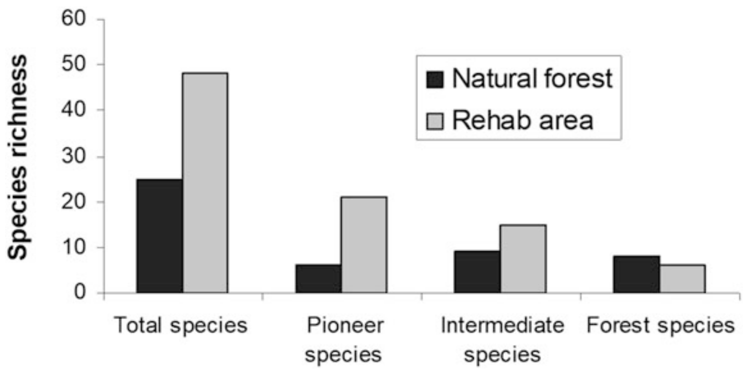


Fig. 1.10 Species richness (total, and by species type) of understory plants in rehabilitated and natural forest areas at Washington Creek (Figs. 1.10 and 1.11 credit Shelley Hunt)

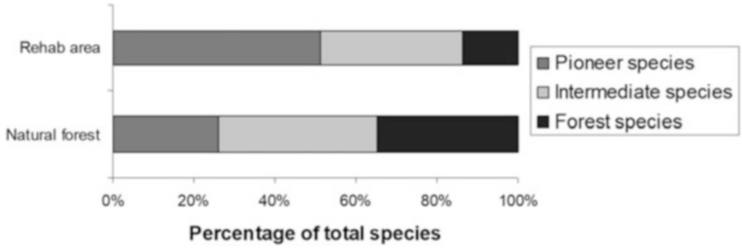


Fig. 1.11 The contributions of different species types to total species richness of understory plants in rehabilitated and natural riparian forest areas at Washington Creek

rehabilitated area, while the deeper shade and lack of recent disturbance ensure that the natural forest area is dominated by forest and intermediate species. There are signs, however, that the rehabilitated area is slowly gaining "forest" characteristics, such as the presence of tree seedlings (*Celtis* spp. and *Juglans nigra*) and other forest or intermediate plants such as hooked crowfoot (*Ranunculus recurvatus*) and jewelweed (*Impatiens capensis*).

1.5.2.3 Fish Diversity

Riparian vegetation influences aquatic communities of streams both directly and indirectly. Secondary effects of vegetation are related to its roles in water temperature control and in mitigating erosion and sedimentation from adjacent croplands, which can adversely affect biological communities. Excessive sedimentation can result in the covering of suitable spawning areas or habitat for fish and invertebrate species, respectively (Erman and Ligon 1988). The direct influence of vegetation on aquatic biota includes increased detrital inputs, food viability, and provision of habitat by in-stream and overhanging vegetation.

General observations by fisheries crews indicate that Washington Creek has had resident brook trout (*Salvelinus fontinalis*) populations along other sections of its length in the past and at present. Brook trout have been collected in the treatment area since rehabilitation work began in 1985 and were found at the control site in 1990. Other species that were present in both areas tended to be found in a majority of the years when samples were collected and included white suckers (*Catostomus commersonii*), Johnny darters (*Etheostoma nigrum*), common shiners (*Notropis cornutus*), and creek chubs (*Semotilus atromaculatus*). Since 1985, the composition of the fish community at the treatment site has appeared to fluctuate more than that of the control site. New species particular to the treatment area included redside dace (*Clinostomus elongatus*), silvery chub (*Semotilus corporalis*), logperch (*Percina caprodes*), and brook trout.

What this implies is that riparian plantings can positively influence the aquatic ecosystems and enhance fish and other aquatic organism diversity. Therefore, these aquatic species diversities can be considered as sustainability indicators to assess the health of aquatic ecosystems as influenced by riparian-based biomass production systems.

1.5.3 Water Quality

The study that was conducted at the Washington Creek during 2006 and 2007 looked at several aspects of water quality, and the results are presented below. The indicators that are discussed below therefore can be considered as sustainability indicators for biomass production in riparian buffers.

1.5.3.1 Nitrate-Nitrogen

Figure 1.12 depicts nitrate-N concentrations in well water ("wells" are 0.75-inch PVC pipes installed in the ground up to the water table for water sampling) collected along transects.

The wells were deployed at 0, 25, and 50 m from the creek. 0 m was situated just adjacent to the creek or the end of the "stream-side" buffer; the 25 m sampling site was at the edge of the "land-side" buffer, especially in the NF and RA land-use systems (Fig. 1.9); and the 50 m well was situated within the agriculture or pasture fields. It is quite evident that the nitrate-N concentration in well water significantly declined as a result of the presence of a vegetative buffer (Fig. 1.12). The nitrate-N concentrations declined up to 88%, 94%, 78%, and 90%, between 50 m and 0 m, in NF, LV, AP, and RA land-use systems, respectively. However, the largest reduction in nitrate-N concentration was demonstrated in the RA land-use system, and nitrate-N concentration was reduced from 12.31 ppm at 50 m to 1.23 ppm at 0 m. Apart from this observation, it is also interesting to note that any form of vegetative buffer (grass or native shrubs, Fig. 1.9) may help to reduce nitrate-N loading to agricultural streams as shown in Fig. 1.12. The nitrate-N concentrations observed in three land-use systems (NF, LV, and AP) were comparatively lower than that observed in the RA. Upland agricultural practices might have influenced these differences in concentrations. Only the agriculture (AP) and rehabilitated (RA) fields had crops, but the remaining two land uses had pasture grass (LV) and native forest (NF) in the upland. The latter two land uses did not get any inorganic fertilizer application, and this might have resulted in lower nitrate-N levels in these land-use systems. Finally, the take-home message is that the presence of a tree-buffer, at least 25 m in width, can mitigate nitrate-N loading to agricultural streams to a greater extent than the presence of other forms of vegetative buffers, especially when the upland nitrate-N concentrations are high.

1.5.3.2 In-Stream Nitrate-N Concentration

Figure 1.13 depicts the nitrate-N concentrations in the stream, measured over a 6-month period and across all four land-use systems.

Figure 1.13 shows that on any given sample date, there were no differences in stream nitrate-N concentrations across all four land-use systems. This may be due to significant loading of nitrate-N upstream. The important take-home message is that reduction in nitrate-N loading, as influenced by the presence of a vegetative buffer, will not influence the stream water nitrate-N concentration if there is significant upstream loading. Therefore, riparian buffers should be situated along entire length of the agricultural stream and not just along one part of the stream.

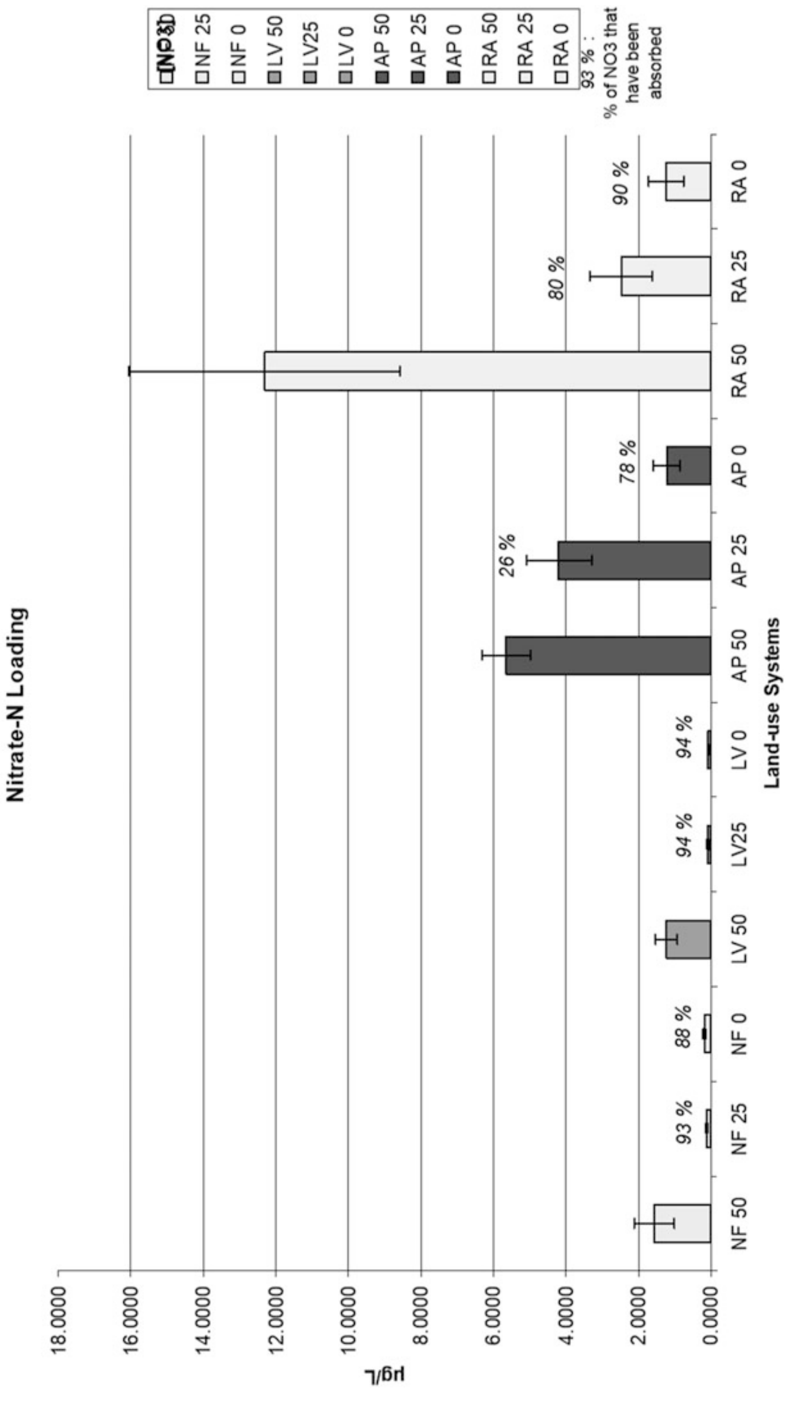


Fig. 1.12 Nitrate-N loading to the stream as influenced by the buffers associated with four land-use systems (From Plascencia-Escalante 2008)

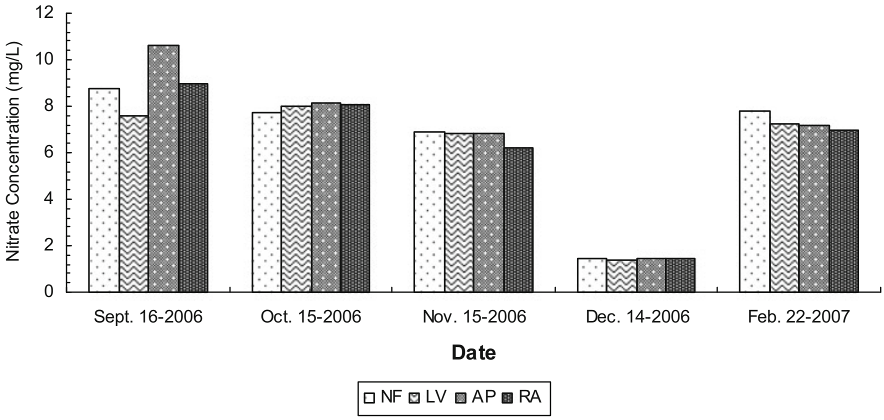


Fig. 1.13 In-stream nitrate-N concentrations across four land-use systems (From Plascencia-Escalante 2008)

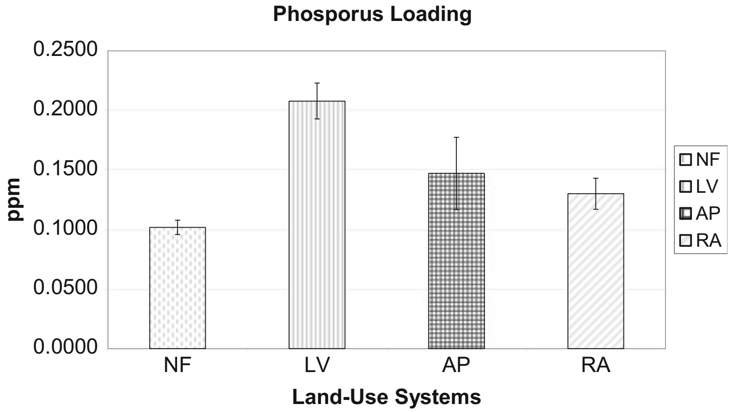


Fig. 1.14 Phosphorus (P) loading to the creek from all four land-use systems (From Plascencia-Escalante 2008)

1.5.3.3 Phosphorus Loading to the Creek

Figure 1.14 depicts phosphorus loading to the creek across all four land-use systems, along all transects, over all sampling dates (May to Dec. 2006).

From Fig. 1.14, it is evident that the livestock land-use system significantly added more phosphorus into the creek than the remaining three land-use systems. The livestock land-use system did not have any tree-buffers. The only vegetation that was present along the creek was the natural grass vegetation, and it appears that grass did not significantly mitigate P loading to the creek. P loading will also depend on the agricultural practices adopted in the upland areas. In this context, if you compare both AP and RA land-use systems, the upland agricultural practices were almost similar as both land-use systems had corn as the agricultural crop. Given that both

(AP and RA) land-use systems had the same crop, the data suggest a slight declining trend in P loading in the RA land-use system. This declining trend may be due to the presence of a tree-buffer in the RA land-use system and the absence of a tree-buffer in the AP land-use system. However, statistically it failed to reach significance (Fig. 1.14).

What this implies is that riparian biomass production adjacent to livestock grazing areas may significantly influence P loading reduction to water sources and thereby enhance the quality of water. Riparian tree plantings therefore have dual purpose: (a) to enhance water quality and (b) biomass production for bioenergy.

1.5.3.4 Periphytons

Figure 1.15 depicts periphyton growth in the stream across all four land-use systems. The two major factors that can influence periphyton growth in the stream are solar radiation and stream water quality. In this verification study, the stream water quality did not significantly differ between the four land-use systems (Fig. 1.13). As mentioned earlier, this perhaps may be due to the upstream loading. However, the tree-buffered ecosystems (NF and RA) significantly shaded the stream (Fig. 1.16).

As a result of this shading effect, periphyton growth was significantly reduced in NF and RA land-use systems when compared with LV and AP land-use systems (Fig. 1.15). The gap fraction for LV and AP land-use systems was 100%, which means that there was no shading as a result of the absence of a tree-buffer. Further from Fig. 1.14, P loading was at its peak in the LV land-use system. Therefore, no shading effect coupled with P loading might have resulted in increased periphyton growth in the creek in the region associated with LV land-use system (Fig. 1.15). Nevertheless, the presence of a tree-buffer can mitigate eutrophication in agricultural streams, as shown in this verification study, by both providing shade (Fig. 1.16) and by reducing P loading (Fig. 1.14).

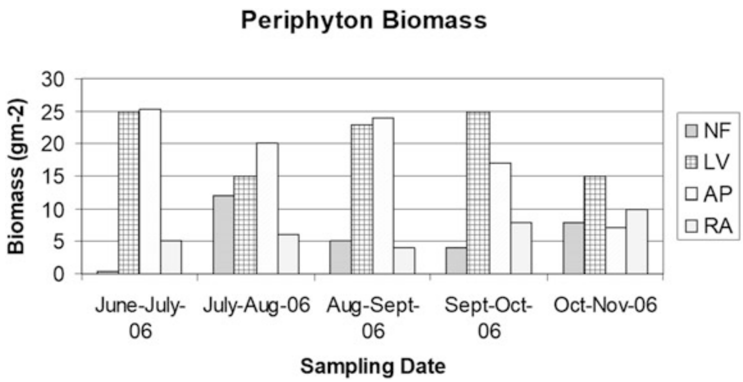


Fig. 1.15 Periphyton biomass quantification in stream, across all four land uses (From Plascencia-Escalante 2008)

	**Natural Forest Transect 2** where periphytons were installed. Pictures were taken on September 10-2006. The only purpose of these pictures is to have an idea how much light was entering to the stream. Total gap fraction: 19.73
	**Natural Forest Transect 3** Total gap fraction: 14.30
	**Rehabilitated Area Transect 1** Total gap fraction: 12.21
	**Rehabilitated Area Transect 3** Total gap fraction: 12.49

Fig. 1.16 Hemispherical picture taken at Washington Creek (September, 2006) under the stream canopy. The bigger the gap fraction, the higher will be the light intensity (From Plascencia-Escalante 2008)

1.5.3.5 Water Chemistry

Figures 1.17, 1.18, 1.19, and 1.20 represent oxygen saturation, water conductivity, hardness, and pH, respectively. Statistically there were no differences on these quantified parameters as influenced by the presence of buffer or land-use systems. Slight variations that are seen may be due to site-specific characteristics. It is also interesting to note that in Fig. 1.15, periphyton growth was significantly higher in LV and AP land-use systems. This condition could have reduced the oxygen

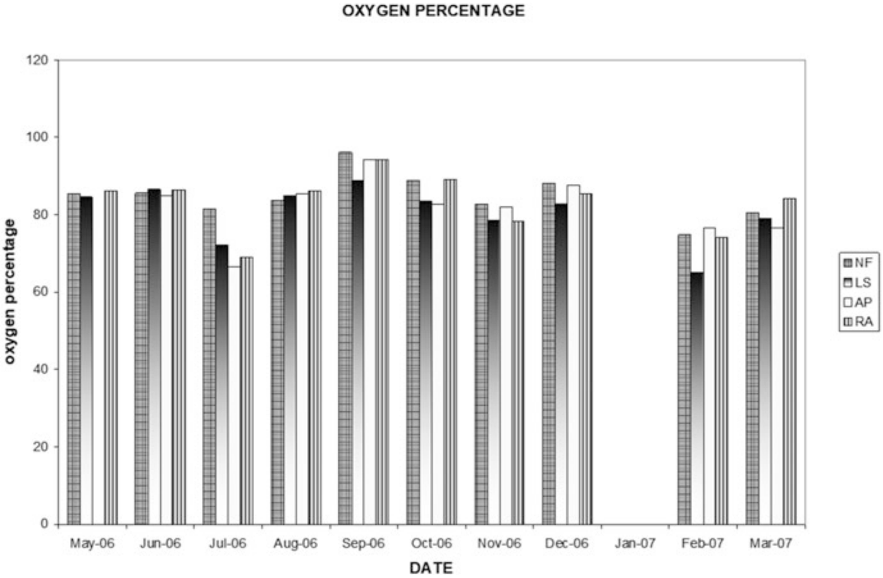


Fig. 1.17 Percentage of oxygen saturation across all four land-use systems, over time (Figs. 1.17, 1.18, 1.19 and 1.20 are From Plascencia-Escalante 2008)

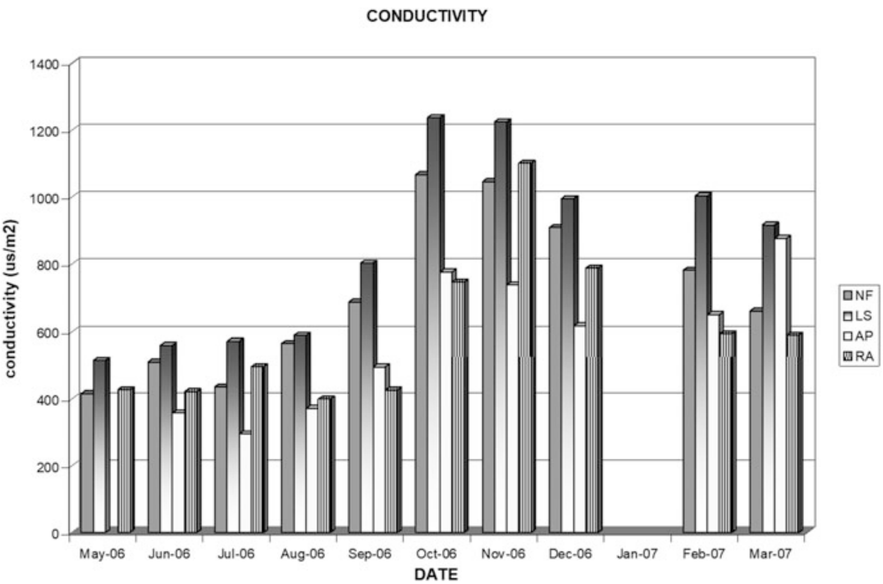


Fig. 1.18 Water conductivity across all four land-use systems, over time

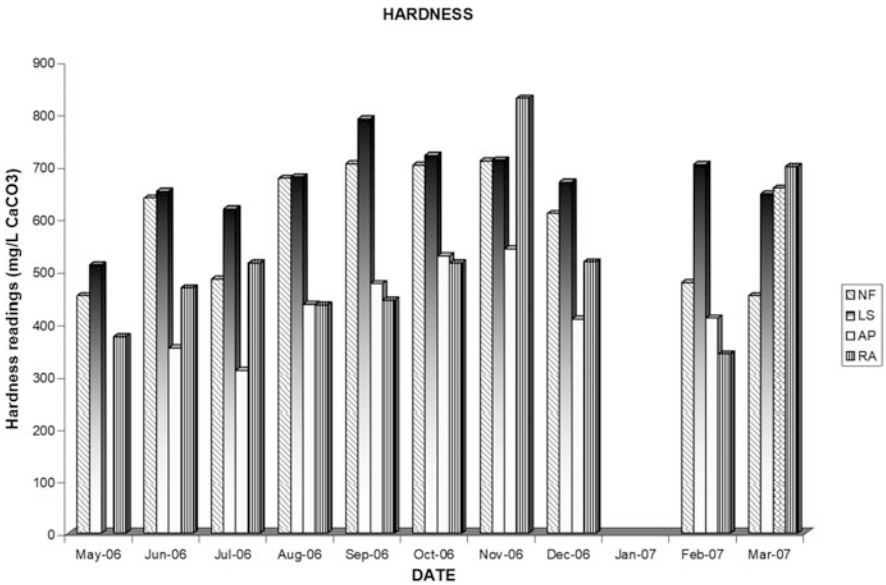


Fig. 1.19 Water hardness across all four land-use systems, over time

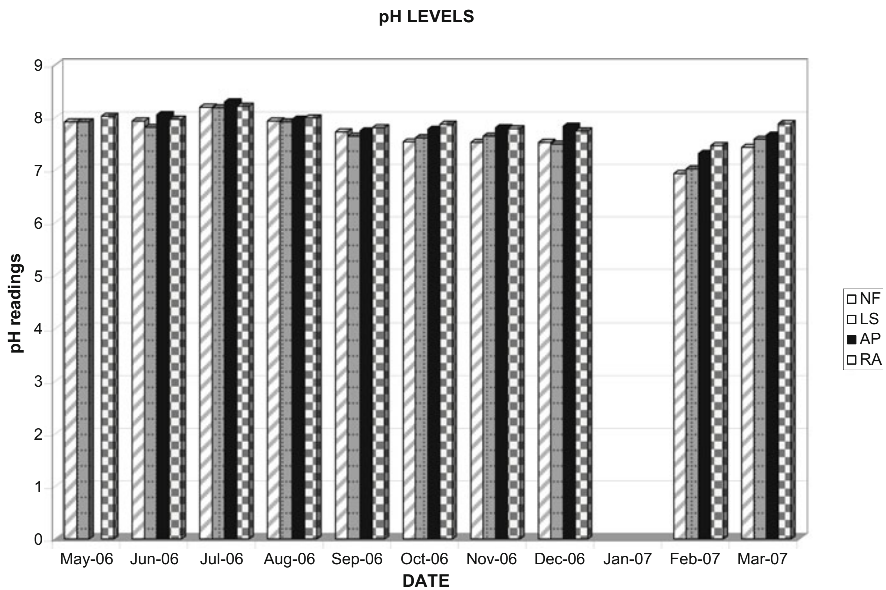


Fig. 1.20 Water pH across all four land-use systems, over time

saturation in water. However, in this verification study, this did not happen. The water depth in the creek along LV and AP land uses was very shallow (less than 0.5 m), and therefore, significant amount of atmospheric oxygen could have got dissolved in creek water.

From the results obtained in this verification study, it appears that tree buffer provided the best results in terms of nutrient loading reduction and periphyton growth reduction. All these parameters normally contribute to eutrophication in degraded agricultural streams. A reduction of these parameters or indicators should therefore provide mitigation strategies and thus enhance the water quality. Therefore, as found in this verification study, all streams or creeks that flow through agricultural lands should have a minimum of 25 m of rehabilitated tree-buffer zone in order to protect and conserve our rural water sources. This tree buffer zone can also be used for biomass production after leaving a few meters from the aquatic environment as protected zone in order to protect streambank stability. Continuous removal of trees for biomass can also enhance subsequent growth of trees and contribute to rapid removal of nutrient from agricultural runoff and thereby maintain and enhance the water quality. The tree-buffers can also enhance carbon (C) sequestration and offset fossil fuel emissions from farm operations, and farms can make a genuine attempt to become carbon neutral as stated above. In addition, the presented water-related sustainability indicators can be quantified, and standard values can be developed based on slope, soil, and environmental factors.

1.6 Conclusions

In this chapter, tree-based intercropping systems and riparian buffer systems were examined for their potential to grow biomass for bioenergy production. Numerous potential sustainability indicators were also examined that are relevant to the two selected agroforestry systems and included quantitative values from the two case studies conducted in southern Ontario, Canada, over a period of 26 years. However, additional research is required in order to develop acceptable standard values for all presented sustainability indicators for these two systems in Canada.

In general, agroforestry systems are considered for their ability to produce diverse products and services. The sustainability indicators that are discussed in this chapter are directly linked to the services rendered by these systems contributing to environmental sustainability. Therefore, biomass production from these systems can be obtained while contributing to environmental well-being and health, including biodiversity, as discussed in this chapter.

Among the temperate agroforestry systems, riparian buffer plantings have the greatest potential to produce biomass while enhancing biodiversity, environmental, and ecosystem services. The reason for this is that the tree density in riparian plantings can be substantially increased over those of other agroforestry systems, as there are no associated annual crops grown under these plantings. In addition, as they are established at the terrestrial-aquatic interface of both lakes and streams, competition for moisture is seldom a limiting factor. They also exert a disproportionate regulatory influence over many important ecological processes—both terrestrial and aquatic in nature—at many scales.

In tree-based intercropping systems, SRWC or herbaceous biomass crops can be grown in between the tree rows. Along the tree rows, however, high-value timber trees can be grown for long-term economic benefits with the SRWC grown in the alleys to generate short-term revenues from biomass production while contributing to environmental services as described in this chapter.

Given the current interest on climate change mitigation strategies, the enhancement of C sequestration in terrestrial ecosystems has been emphasized and has also been promoted as a potential mitigation strategy. In this context, agroforestry-based biomass production systems can play a major role in sequestering atmospheric CO_2. However, as the aboveground biomass is utilized for energy production, C tied up in the aboveground biomass is lost during energy utilization either through combustion or biochemical and thermochemical processes. Therefore, in these production systems, the emphasis should be on belowground C sequestration in roots and in soils.

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2 Management Practices Vis-a-vis Agroforestry for the Improvement of Rangelands of Jammu and Kashmir in Northwestern Himalaya, India

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Abstract

The Northwestern Himalayan region exhibits a diverse climate, topography, ecology, plant community, and land use type. The average annual precipitation varies from 80 mm in Jammu and Kashmir (Ladakh) to 200 cm in Himachal Pradesh and Uttarakhand. Livestock rearing is a substantial source of income for the people in this region, who practice both sedentary and migratory systems of livestock grazing. The livelihood of almost 25% of the population of Jammu and Kashmir (J&K) including nomads and semi-nomads, namely, Gujjars, Bakerwals, Chopans, Changpas, and Gaddis, depends wholly or partly on rangelands. There are concerns about the sustainability of livestock grazing systems and the integrity of pastoral ecosystems. Controlling the time, duration, and intensity of grazing appears to be the key factor in grazing management. The forages like red clover, white clover, tall fescue, orchard grass, sain foin, lucerne as well as tree fodder are commonly used for feeding the livestock. Due to recent land use changes, the resource base of grazing and pasture lands have deteriorated causing an imbalance in the demand of fodder due to heavy livestock population and supply of various fodder species. Agroforestry systems including silvopastoral, agri-silvicultural, agri-horti-silvicultural, and horti-pastoral systems have recently been introduced to improve the degraded grasslands as well as to improve fodder availability. This chapter aimed to discuss the status of temperate rangelands/pastures and factors causing degradation of the grasslands and to suggest suitable management practices vis-a-vis agroforestry and other

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sustainable practices to improve the existing grasslands in western Himalaya with special reference to Jammu and Kashmir.

Keywords

Agroforestry · Degraded lands · Temperate grasslands · Nutrient cycling · Overgrazing · Pastures

2.1 Introduction

Grassland ecosystems are ecologically and economically important and occur widely in different regions of the world. The grasslands provide both tangible and intangible services to the human society such as feed for livestock and the regulation of carbon and water cycling. Grasslands (rangelands) provide forage and habitat to domestic animals and wildlife as well. Most grasslands have coevolved with large grazers, and herbivory has affected ecological processes at levels ranging from individual plants to ecosystem processes and landscape patterns (Blair et al. 2014). Furthermore, the grassland soils store large quantities of carbon and other nutrients and play a major role in biogeochemical cycles. Temperate grasslands are the third largest global store of carbon in soils and vegetation after wetlands and boreal forests.

In terms of livelihood dependency, it is estimated that about one billion people depend directly on grasslands for their livelihoods worldwide (Suttie et al. 2005). Owing to this heavy dependence, grasslands are among the most critically endangered biomes due to widespread conversion for multiple anthropogenic uses, including 70% of global agriculture (Hoekstra et al. 2005), besides increased pressures from people and livestock populations. In India, grasslands generally occur in areas receiving 250—900 mm annual precipitation. There are a variety of grassland types with different dominant plant communities in India, in response to the variability in environmental conditions in each of the grassland types (Gupta and Singh 1982).

Temperate pastures/grasslands are typically very productive; they are characterized by well-developed soils, with medium to high precipitation. Temperate areas are situated in an altitudinal range of 1000–4500 m above mean sea level and thus exhibit a remarkable diversity. The livestock population in the temperate Himalayan region has increased tremendously during the last three decades and is 21.33 million against human population of 29.53 million. In order to feed 21.33 million cattle in Northwestern Himalayan states, 1.35 million tons of fodder is required. Grasslands of the Kashmir valley known for their aesthetic, biological, and cultural values are being subjected to varied disturbances like grazing, mowing, trampling, etc., owing to overgrazing, and as such, degradation of pastures has achieved critical dimensions all across the globe. The region does not produce adequate fodder and, therefore, faces 54% deficit in green fodder and 34% deficit in dry fodder. The major part (62.2%) of the fodder is extracted from forests (tree/

shrub/leaves and herbaceous ground flora). The remaining fodder (37.8%) is derived from agroforestry systems, low-altitude grasslands, degraded lands, high-altitude grasslands, and crop residues. Strategies like planting fodder trees or grasses in the waste/degraded lands which represent 7.9, 9.8, and 11.5% of geographical area in Himachal Pradesh, Jammu and Kashmir, and Uttarakhand, respectively, are needed for enhancing the fodder production. It is also needed to plant grasses, fodder bushes, and wild fruits on the forest floors to feed the wildlife and the livestock of the pastoralists during their journey from alpines to the lower hills (VPKAS 2011). In addition, farm spaces on terrace and improved crop production technology coupled with integration of agroforestry will help in bridging the gap between demand and supply of the fodder. The Himalayan region of India is presently under heavy stress on account of a large-scale exploitation for fuelwood, timber, and fodder; mismanagement of forest resources; and frequent fires. There is acute shortage of fodder, especially green nutritious fodder, which is the major cause of low productivity of the livestock, especially in hilly areas.

This chapter discusses rangeland and pasture resources of Jammu and Kashmir, human impacts on grasslands, grassland management, and agroforestry approaches for the improvement of degraded grasslands.

2.2 Rangeland and Grassland Resources

Coupland (1992) defined grassland as "ecosystems in which the dominant vegetative component is comprised of herbaceous species." Sometimes, the term grassland is used to include herbs and shrubs. Grasslands (rangelands) provide forage and habitat to domestic animals and wildlife. As mentioned earlier, grasslands rank among the most critically endangered biomes due to widespread conversion for multiple anthropogenic uses, including 70% of global agriculture (Hoekstra et al. 2005), besides increased pressures from people and livestock populations (Suttie et al. 2005). Such a rapid change in grassland forest interface was reported by Tiwari and Joshi (2015) in low and mid-Himalayan ranges of Kumaun region where more than 15% of the total Dabka watershed changed its land use from 1982 to 2012 mainly due to human encroachments of grasslands. In 1982, grasslands constituted 15.1% of land use type, whereas in 2012, the percentage decreased to 11.7%.

Rangelands are geographical regions dominated by grass and grass-like species with or without scattered woody plants, occupying between 18 and 23% of the world land area excluding Antarctica. Rangelands are home both to significant concentrations of large mammals and plants with a high value in both leisure and scientific terms and to human populations that have historically been excluded and marginalized, pastoralists and hunter-gatherers (Blench and Sommer 1999). The biophysical and socioeconomic functions of rangelands must be measured and reported in order to maintain rangelands in good condition. This involves the monitoring of development procedures and the transfer of information to stakeholders.

According to White et al. (2000), grasslands cover 40% of the earth's surface and are found in every region (excluding Greenland and Antarctica) of the world but most commonly in semiarid zones (28% of the world's grasslands), followed by humid (23%), cold (20%), and arid zones (19%). Sub-Saharan Africa and Asia have the largest total area of grassland. Areas around the world with arid, semiarid, and dry subhumid climates, where topography and soils are not suitable for large-scale agriculture, are generally referred to as rangelands, since these areas are traditionally used for pastoralism (Harrington et al. 1984).

Dabadghao and Shankarnarayan (1973) classified grasslands of India into five types, namely, *Sehima-Dichanthium*, *Dichanthium-Cenchrus-Lasiurus*, *Phragmites-Saccharum-Imperata*, *Themeda-Arundinella*, and temperate-alpine grassland types. The Himalayan region falls in the last category. The area is above 2100 m and includes the temperate and cold arid areas of Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, West Bengal, and the northeastern states. The principal grass species of the region are *Agrostis filipes*, *Agrostis canina*, *Poa pratensis*, *Agropyron canaliculatum*, *Chrysopogon gryllus*, and *Phleum alpinum*. These are "highly nutritious forages." Management interventions include the use of fertilizers to improve grass quality and quantity. Other intensive management measures, such as reseeding and the introduction of vegetables, can also be taken on a large scale to improve the overall area. Shankar and Gupta (1992) classified the Indian grazing lands as fragile ecosystems and have ranked classes IV and V in their land capability classification. The carrying capacity of these areas is 0.20 to 1.47 adult cattle units (ACU) ha^{-1}, but the present stocking rates are much higher. In semiarid areas, the present stocking rates are 1 to 51 ACU ha^{-1}against the carrying capacity of 1 ACU ha^{-1} (Shankar and Gupta 1992), while in arid areas, the stocking rates are 1 to 4 ACU ha^{-1} against the carrying capacity of 0.2–0.5 ACU ha^{-1} (Raheja 1966).

2.2.1 The Rangeland/Pasture Resources of Jammu and Kashmir

Jammu and Kashmir (J&K) consists of four categories of fodder diversity based on the agro-climatic zones, i.e., temperate (*Trifolium repens*, *Avena sativa*, *Plantago major*), intermediate (*Cynodon dactylon*), subtropical (*Oxalis corniculata*), and cold arid zone (*Panicum miliaceum*, *Medicago sativa*, *Carex* spp., *Hippophae rhamnoides*) (Singh et al. 2018). Jammu and Kashmir's paradox is that the state support lands (rangelands, pastures, wastelands, forests-ICIMOD) and their large natural resource base provide crucial livelihoods from these resources. However, the integration of the remaining economies of these areas/lands into the monitored economy has led to such changes in livelihood systems that require increased support for grazing/food from these lands. This framework will be helpful to the development of different types of livelihood systems dependent on fodder and will provide solutions to fodder and grazing problems at both local and international level.

It is estimated that farming households would need access to support lands ideally in the ratio of 1 hectare of cropland to sustainable livelihoods in hilly areas for crop

Table 2.1 Region-wise requirement and availability of fodder (million Mg on DM basis)

S. no.	Region	Requirement	Availability	From all sources % deficiency
01	Jammu	10.01	5.41	45.94
02	Kashmir	4.40	2.01	54.35
03	Ladakh	0.41	0.14	69.44
Total		14.82	7.56	49.17

Source: Statistical Digest J&K (2008–2009)

livestock to 12 hectares of support lands (pastures and rangelands). This need for area for pure pastoral farming communities is based on the capacity of land resources and livelihoods (Table 2.1). Information on the average pattern of animal units' consumption of fodder is well researched and available. The amount of access to support lands (pastures) per animal head in the Jammu, Kashmir, and Ladakh divisions of the state of J&K ranges from 0.02 hectares in the Greater Himalayan range of Ladakh to 0.34 hectares in the middle Himalayan mountains of Jammu under traditional agriculture. In Kashmir Himalayas, temperate pasture lands of 0.143 and 0.064 ha per capita of livestock are available in Kashmir and Jammu province, respectively.

In fact, 82% of the state of J&K falls under the category of non-cropland; the resulting small holdings and vast pasture lands enabled farmers to develop different livestock crops or livelihood systems based on livestock. The livelihood of almost 25% of the population of J&K including nomads and semi-nomads, namely, Gujjars, Bakerwals, Chopans, Changpas, and Daddies, depend wholly or partly on support lands (rangeland and pasturelands) based on pastoral or agro-pastoral systems, whereas the remaining 75% of farming families also have mixed farming systems for crop livestock.

Grazing livestock farming is an important economic activity of the state and has a significant share in the economy (9% of state GDP). Sheep and goats, which make up 60% of the livestock, are mainly raised under the animal production pastoral system. The state has more than 61% of its forest geographical area and widespread pastures to support large domestic and wildlife populations. The importance of pasture in livestock-based farming families in the state is visible from the ratio between humans and animals, which is currently 1:1, and livestock contributes approximately 9% of GDP higher than the horticultural sector. The limited factors of the livestock sector, as of the subsistent economy, include low animal productivity, limited feed supplement, and lack of mechanisms for disease management.

An assessment of the major animal production constraints (growth-based livelihoods) in three regions of J&K and the opportunities for increased productivity concludes that nutrition is by far the most important factor and has been an acute problem for a long time. The available fodder and feed resources in the form of pastures and meadows if fully utilized can optimize the productivity. Due to high grazing pressure and little time for regeneration, many palatable species of grass and legumes have disappeared, and as a result, pasture productivity has declined considerably in most pastures, mainly covered by obscure weeds such as *Euphorbia*

Table 2.2 Current livestock population and feed/fodder requirement for J&K (2008–2009)

S. no.	Animal species	Region	Numbers (million)	Dry fodder 180 days	Concentrate 365 days basis	Concentrate 180 days basis
01	Cattle	J K L	1.88 1.48 0.04	41.17 32.43 00.92	20.58 16.22 0.46	10.15 08.00 0.27
Total			3.40	73.52	37.26	18.42
02	Buffaloes	J K L	1.06 0.02 –	31.13 – 0.64	15.35 – –	5.57 0.12 –
Total			1.08	31.77		5.69
03	Sheep	J K L	2.63 1.35 0.24	14.40 7.40 1.34	– – –	2.36 1.22 0.22
Total			4.28	23.14	–	3.80
04	Goats	J K L	1.65 0.26 0.21	9.00 1.46 1.17	– – –	1.48 0.24 0.19
Total			2.13	11.63	–	1.19
05	Equines	J K L	0.13 0.06 0.01	3.80 1.90 0.40	1.42 0.71 0.14	0.70 0.35 0.07
Total			0.20	6.10	2.27	1.12
06	Yak/mithun	J K L	0.02 0.01 0.04	0.42 0.12 0.85	0.19 0.05 0.43	0.10 0.27 0.21
Total			0.07	1.47	0.76	0.58
07	Camel	J K L	0.0050 – 0.0002	0.10 – 0.07	0.07 – 0.003	0.04 – 0.002
Total			0.0052	0.19	0.073	0.042
Grand total			11.1742			

Source: Statistical Digest J&K (2008–2009)
J, K and L stand for Jammu, Kashmir and Ladakh regions, respectively

prostrata, *Rumex nepalensis*, *Datura stramonium*, and *Urtica dioica*. Ecologists and conservationists have expressed deep concern about the sustainability of livestock grazing in these areas and pastures in Kashmir and about the preservation of the integrity of pastoral ecosystems. Fragmentation of meadows and habitat degradation give a poor picture of unsustainability.

The available region-wise data from government agencies about the state of affairs of demand and supply of forage and fodder are given in Tables 2.1 and 2.2.

Requirements were calculated on average basis as per feeding schedules taking into consideration all age groups and all physiological phases of animal, i.e., growth, milk, wool, production, and pregnancy.

2.3 Fodder and Forage Production

Livestock rearing is an integral part of economy in the rural part of the Himalaya. Grasslands are the main feed resource of this activity in the economy of Himalayan. The major part (62.2%) of the fodder is extracted from forests (tree/shrub/leaves and herbaceous ground flora). The remaining fodder (37.8%) is derived from agroforestry systems, low-altitude grasslands, degraded lands, high-altitude grasslands, and crop residues. The Indian subcontinent is one of the richest hot spots in the world with a rich biodiversity. For instance, Himalaya supports about 84 species of trees and 40 species of shrubs having fodder value, yet not more than 20 species of trees are extensively used by farmers (Meena and Singh 2014).

The distribution of different grass species has been influenced by climate, topography, physiographic factors, altitude, and related aspects. The grasslands in mid and low elevations represent a range of successional stages and thus can be named as sub-climax or disclimax entities (Melkania 1995). Although animal husbandry is an important occupation of farmers in the area, the cultivation of forage has been almost neglected. The Himalayas' natural resources have been exploited in an unplanned manner for centuries, leading to degradation. The careless cutting of trees, the indiscriminate use of pasture areas, and the absence of rehabilitation programs have led to the denudation of hill slopes, which have resulted in a critically low availability of biomass and adverse effects on animal production. The productivity of livestock is therefore very low, and all the Himalayan states must import different livestock products from the plains.

2.3.1 Present Status of the Forage Production in Western Himalaya

Misri (1988) studied the biomass availability of some of the representative pastures of Kashmir Himalaya and found that green herbage availability varied from 4.7 to 29.1 Mg ha^{-1}. In Himachal Pradesh, the green herbage availability varied from 1.5 to 1.74 Mg ha^{-1} in temperate pastures and 0.5 to 1.0 Mg ha^{-1} in alpine and subalpine pastures (Singh 1995). Ram and Singh (1994) observed that biomass availability varied from 1.62 to 3.96 Mg ha^{-1} (green herbage) in Himalayan pasture of Uttar Pradesh. Tingcheng and Yuangag (1989) reported the stocking capacity of central Himalayan pastures between 0.4 and 13.3 sheep ha^{-1} $annum^{-1}$ under natural vegetation in alpine steppe, meadows, and alpine meadows. In cold and temperate grasslands of semi-natural grasslands, the stocking capacity varied from 0.6 to 1.9 sheep ha^{-1} $annum^{-1}$. Melkania and Singh (1989) estimated that net above-ground biomass varied from 279 to 1568 g m^{-2} for low elevation Himalaya, 219 to 285 g m^{-2} for mid-elevation Himalaya, and 233 to 372 g m^{-2} for high elevation Himalaya. Forage cultivation is restricted to only about 1% of the cultivated area in the entire Himalayan region (Table 2.3). This is basically because of the preponderance of marginal and small land holdings in the area. Besides grazing and fodder trees, the major local forage resource is the crop residue, which again is too inadequate to sustain the livestock. In the state like Himachal Pradesh, there exists a gap of about 35.0 and

Table 2.3 Projected scenario of feed and fodder availability and future requirement (in million Mg)

Year	Supply		Demand		Deficit (%) of demand (actual demand)	
	Green	Dry	Green	Dry	Green	Dry
1995	379.3	421	447	526	59.95 (568)	19.95 (1050)
2000	384.5	428	988	544	61.10 (604)	21.93 (121)
2005	389.5	443	1025	569	61.96 (604)	22.08 (126)
2010	289.9	451	1061	584	61.96 (635)	23.46 (138)
2015	395.2	466	1097	609	62.76 (666)	23.56 (143)
2020	400.6	473	1134	630	64.21 (728)	24.81 (157)
2025	411.3	488	1170	650	64.82 (759)	24.92 (162)

Source: Planning Commission, Draft Report of Working Group on Animal Husbandry and Dairying for Five-Year Plan (2002–2007, Govt. of India, Planning Commission, August-2011)

57.0% from dry and green forages, respectively. Every year on an average, about 7450 Mg of wheat straw is imported annually from the neighboring states (Vashist et al. 2000).

2.3.2 Livestock Scenario

The livestock population in the region has increased tremendously during the last three decades and is 21.33 million against human population of 29.53 million. In order to feed 21.33 million cattle in Northwestern Himalayan states, 1.35 million tons of fodder is required. The region does not produce adequate fodder and, therefore, faces 54% deficit in green fodder and 34% in dry fodder (VPKAS 2011).

2.4 Grassland Management Strategies

Keeping in view fodder supply, demand, and fodder production, in order to overcome the gap between demand and supply, the emphases need to be given on several steps for augmenting the fodder production. Existing resource utilization pattern needs to be studied in totality according to a system approach. Fodder production is a component of the farming system, and efforts need to be made for increasing the forage production in a farming system approach. The holistic approach of integrated resource management will be based on maintaining the fragile balance between productivity functions and conservation practices for ecological sustainability. The strategies for improvement and conservation of Himalayan resources, particularly the forage resources, will have to be dictated by actual customers—the native inhabitants of the region. Some of the scientific interventions, which could help in improving the productivity of forages, are described here.

2.4.1 Agronomic Management

The herbage production from grasslands and meadows can be enhanced with the adoption of improved technology. Important components of this technology are the following:

(a) Control of bushes and weeds
(b) Pasture establishment
(c) Introduction of legumes/grasses
(d) Fertilizer application
(e) Cutting and grazing management
(a) Control of bushes and weeds
    The bushes and noxious weeds and poor quality grasses may offer severe competition for light and nutrients. The most common obnoxious weeds of the Himalayan grasslands are *Lantana camara*, *Ageratum conyzoides*, and *Eupatorium adenophorum*. These weeds can be controlled by cutting, and stems are treated with herbicides to prevent regrowth. The herbicides like Weedon 64, Picloram, Paraquat, and Glyphosate at 1.0–2.0 kg ha^{-1} could be applied around the bush. Sood and Singh (1986) found that paraquat spray in the 15 cm band at 0.6 lha^{-1} reduced the weed incidence in the grasslands and the fresh herbage yield increased by 26.8%.
(b) Pasture Establishment
    The successful establishment of a pasture requires more skill and care, as compared to other crops. The method of introduction of improved grasses and legumes in the natural grasslands should be cost-effective with minimum soil working. The following methods of establishment could be considered.
    (i) Scratching or Pitting
        Planting Nandi grass (*Nandi setaria*) and Guinea grass (*Megathyrsus maximus*) in circular pits was superior over local practice (Singh 1995). Similarly, Sood and Kumar (1996) also found that pit method of introduction is superior to scrapping.
    (ii) Hoof and Teeth Method
        The pasture could be heavily grazed, followed by throwing seeds and then allowing the animals to trample the area when soil is wet.
(c) Introduction of Legumes/Grasses
    Forage legumes are important because they enrich the nitrogen content of the soil and have a high nutritive value. Legumes can be grown in mixtures with grasses in grasslands. They supply associated grasses with nitrogen and thereby contribute to the conservation of energy by reducing the need for N fertilization. By introduction of legumes, the quantity as well as quality of herbage production can be substantially increased. Among the legumes, siratro (*Macroptilium atropurpureum*), *Stylosanthes hamata*, *S. scabra*, *Glycine javanica*, *Dolichos axillaris*, *Desmodium* spp., and *Centrosema pubescens* have shown good performance (Melkania 1995). Indigenous legumes such as clovers (*Trifolium pratense*, *T. repens*), *Medicago denticulata*, *Melilotus albus*, white clover

(*M. alba* var. Ladino and Louisiana), and red clover (*Trifolium repens*) var. Montgomery have proved successful in Kashmir Valley apart from lucerne (*Medicago sativa* cv. T-9 and Hunter River) and berseem (*Trifolium alexandrinum*) (Gupta 1977). Legumes and grass species can be introduced during July by seeding and tussock planting, respectively. A combination of Siratro has been found quite successful for the mid altitude region (Mlay 1987). The herbage yield and nutritive value of the hay from grasses-legume mixtures were found five and two times higher, respectively, than the hay of local species. It is essential that during the first year of seeding/tussock planting, grazing is restricted in treated sites and the grass cutting is done carefully to help the establishment of introduced fodder species.

Some of the grasses like *Cenchrus ciliaris*, *Dactylis glomerata*, *Dichanthium annulatum*, *Festuca* sp., *Lolium* sp., *Pennisetum pedicellatum*, etc., and legumes such as *Desmodium intortum*, *Dolichos lablab*, *Phaseolus atropurpureus*, *Stylosanthes humilis*, and *Trifolium* sp. have been found adapted to different agro-climatic regions of Indian Himalaya (Shastry and Patnaik 1990).

Legumes introduced in the pastures generally do not establish well due to ineffective nodulation. Hazra (1998) observed that the *Rhizobium* inoculation of the pasture legumes provides synergistic effect for better establishment and obtained 59% and 72% higher green and dry herbage yield as compared to control.

(d) Fertilizer Management

The present poor production potential of pastures could also be attributed to poor fertility of soils. To raise the fertility status and rectify the deficiencies, soil testing coupled with field trials needs to be conducted to work out the fertilizer requirement of different pastures. Generally, no fertilizer is added to rangelands except the dropped excreta by animals. Judicious use of fertilizer for pasture can boost the vegetative growth and is also economically feasible. Application of nitrogen fertilizer must be given in split doses for better utilization, whereas phosphorus and potash should be supplied as basal dose in case of grasses. In legumes, the full dose of nitrogen, phosphorus, and potash should be given as a basal dose in furrows or by broadcasting at the time of sowing. Dogra et al. (1997) found 120 kg N ha^{-1} and 40 kg P ha^{-1} as the most economical dose. Herbage yield increased significantly with the application of nitrogen at 60 kg ha^{-1} and phosphorus at 30 kg ha^{-1} (Sood and Sharma 1996). Nitrogen at 40 kg ha^{-1} and phosphorus at 30 kg ha^{-1} applied as basal and two splits (onset of monsoon and 45 days after the first application) in natural grassland increased the forage yield significantly. Two splits were significantly superior to single application (Singh 1995). The experiments on N and P requirement in Himachal Pradesh reveal that application of 80 kg ha^{-1} each of nitrogen and phosphorus was found to be the best for increasing the forage yield (Sood and Bhandari 1992).

(e) Cutting and Grazing Management

The response to cutting of a forage plant depends upon its seasonal yield of carbohydrate storage, its growth habit, and extent of inflorescence development.

Frequency of cutting also significantly influences the yield and quality of herbage produced. The areas with high temperatures may require larger interval and low intensity of cutting to build up sufficient carbohydrate storage for regrowth. Singh et al. (1993b) concluded that tall fescue (*Festuca arundinacea*) produced highest dry matter when it was cut at a 30-day interval during second year. Cutting grasses twice from natural grasslands recorded higher fresh forage yield (14.54 Mg ha^{-1}) than one cut (12.08 Mg ha^{-1}) and three cuts (13.30 Mg ha^{-1}). The crude protein content was higher with two cuts compared to one cut (Kaul and Sood 1986). Studies undertaken by Singh (1995) on cutting management of grasslands suggest that the herbage biomass yields can be doubled if harvested twice during July–October.

The Himalayan grasslands experience intense grazing pressure on account of being the prime source of forage. Grazing contributes more than 50% of the herbage requirement for sedentary and semi-migratory flocks, while for migratory flocks, 100% herbage is provided by grazing. Controlling the time, duration, and intensity of grazing appears to be the key factor in grazing management. Periods of rest allow grazed perennials to replenish leaf area and seed set and store food reserves in their roots (Merrill 1983; Adams et al. 1991). Continuous or too frequent access by large numbers of cattle to the same range impedes the ability of new growth to store food. The grazing can lead to the disappearance of nutritive species and infestation by less palatable species and weeds. Deferred rotational grazing system was found superior in *Sehima*-dominated grasslands (Upadhyay et al. 1971), resulting in greater number of animal days as compared to continuous approach. Rotational grazing has steadily gained popularity in the last two decades, because it offers better control over livestock distribution and feeding pattern with goals of periodically resting vegetation (Adams et al. 1991).

2.4.2 Growing of Fodder Crops and Fodder Trees

For augmenting fodder availability, emphasis needs to be given to cultivated fodder crops on large area. Important fodder crops of temperate region include *Avena sativa*, *Brassica* spp., *Medicago sativa*, *Pisum sativum*, etc. (Singh 1987). Foliage of fodder trees could be fed to the livestock in mixture with crop residues and hay. Mixing of tree foliage with dry roughage improves their palatability and nutritive value. Shankar and Singh (1997) and Singh (1982) have suggested the different fodder trees for subtropical Himalaya and subtemperate Himalaya, e.g., species of *Populus*, *Salix*, *Morus*, *Grewia*, etc.

2.5 Silvopastoral Agroforestry Systems for Improving Rangelands

Silvopasture implies sustained and combined management of the same land for herbaceous fodder, top feeds, and fuelwood, thereby leading to optimization of production. The Himalayan rangelands exhibited enormous gain in forage production over existing situation due to multi-tier silvopasture techniques amalgamated with an adaptable complementary plant species. Silvopastoral systems are the most important for increasing fodder production from the marginal, submarginal, and other wastelands, which comprise about 50% of the total land area. It involves planting of multipurpose trees in the existing pastures/grazing lands or planting such trees on wasteland/denuded lands followed by sowing/planting of grasses and or legumes in between the interspaces of trees (Fig. 2.1). Atul (1996) reported 5–7 Mg ha^{-1} green fodder under silvopastoral system, where it was only 3–-4 Mg ha^{-1} without a tree component. Sharma and Koranne (1988) found maximum production of 300 g m^{-2}annum^{-1} under the existing grasslands, while under modified network of silvopastoral system of grass *Digitaria decumbens* + tree (*Bauhinia purpurea*/*Quercus incana*/*Grewia optiva*/*Celtis australis*), the production varied from 1800 to 2450 g m^{-2}annum^{-2}.

Fig. 2.1 Poplar-based silvopastoral system

2.5.1 Agri-silvipastoral System

Under the agri-silvicultural system, multipurpose trees (MPTs) including fodder-cum-fuel trees can be grown in association with crops. Trees are pruned annually, yielding fodder as well as fuelwood. In addition to annual pruning, few trees are also cut down in order to allow light penetration and minimization of competition with the crops. Under alley cropping system, MPTs like *Leucaena leucocephala* and even perennial pigeon pea are pruned frequently to provide leaf fodder to get better crop production.

2.5.2 Agri-horti-silvicultural System

Under this system besides growing fruit trees and fodder crops, fast-growing NFTs like *Leucaena leucocephala* can be lopped two to three times in a year to provide fodder (2.5–3.0 Mg ha^{-1}) and fuelwood (1.8–2.5 Mg ha^{-1}). These fodder trees also provide some protection to the fruit trees during summer and cold winters.

2.5.3 Horti-pastoral Systems

In this system, forage crops are grown in wide interrow spaces of fruit trees for economic utilization of orchard lands. Horti-pasture up to an elevation of 2000 m is catching up with the orchardist. Forage from horti-pasture is consumed fresh and is also conserved as hay for winters. Sharma and Jindal (1989) found that the introduction of fescue grass in apple orchard gave 83.5% higher fodder yield over local grasses in Shimla hills of Himachal Pradesh.

There is considerable area under orchards in temperate regions. Interspaces between fruit trees could be utilized for the production of fodder by growing perennial grasses and legumes. In U.P. hills, Singh (1995) reported that ryegrass (*Lolium perenne*) and orchard grass (*Dactylis glomerata*) are the best perennial grasses for introduction in apple orchards (Fig. 2.2). Soil N buildup was maximum with white clover introduction.

2.6 Forage Production in Various Land Use Systems

Singh et al. (1993a) recommended various interventions that may find place under different land use systems and have also reported their potential to produce green forage from experimental findings. Some of the examples are as follows.

A noncompetitive land use system for forage production in the hills is to grow forage on terrace bunds and risers (Singh et al. 1993b). Forage grasses/legumes/fodder trees grown on terrace risers and bunds arrest the nutrient loss in runoff water under high rainfall conditions of this region. This gives an added advantage to produce forage without any fertilizer or manure.

Fig. 2.2 Apple-based horti-pastoral system

2.7 Grassland Improvement Techniques

The main objective is to secure maximum production of livestock without any detrimental effect to the productivity of grassland. It is, therefore, essential to see the grassland under consideration is kept at its level of productivity for as long as possible. Decline of herbage productivity may be due to bad drainage or lack of sufficient nutrients in soil or overgrazing.

The methods adopted for improvement will be mainly mechanical, designed to remove excess water from soil. Nutrients and physiological defects may be caused by lack of any one or more of essential plant nutrients. Continued removal of grass cover and consequent leaching may deplete soil nutrients; they become limiting factors in growth of vegetation. In such cases, productivity of grassland can be restored only by applications of nitrogenous and phosphate fertilizers to supply deficient elements.

(a) Weed Control (Bush Control)
Both herbaceous and shrubby weeds such as *Lantana camara*, *Ageratum conyzoides*, and *Eupatorium adenophorum* are found to invade deteriorated grasslands. To eradicate the weeds, various methods like cutting, digging out, burning, or the use of weedicides can be adopted.

(b) Burning of Grasslands
Setting fire to dry vegetation in order to encourage new growth after next monsoon rain is a widespread practice in many parts of India. It is also helpful in eradicating undesirable weeds and shrubby growths that may compete with desirable grasses and legumes (Bond and Keeley 2005; Mucina and Rutherford 2006). Burning is also helpful in encouraging an early spring growth of grasses

and discouraging encroachment of jungle growths. In humid high rainfall areas, burning may not be very harmful, but in semiarid region, burning is definitely harmful.

(c) Enclosure of Grasslands
Elimination of grazing factor, which is directly responsible for deterioration of grasslands, induces a progressive succession. Closure for 4 or 5 years will be effective to serve as seed sources (Liu et al. 2015). Previous studies had indicated that fencing could significantly change species composition, improve soil physicochemical properties, and promote ecosystem resilience (Li et al. 2017). Moderate time fencing (11–13 years) could improve some plant properties and soil nutrients, while 22–24 years of long-term fencing might cause a decreasing trend of those vegetation and soil indexes which indicated the re-degradation of grassland ecosystem. Additionally, seasonal fencing grassland (11–13 years) was better to maintain biodiversity (Liu et al. 2019).

(d) Reseeding
On highly degraded grasslands, the surest and quickest way of regeneration is reseeding, but the topography of the land will be an important consideration in undertaking the reseeding operation (Godfrey 1979; Kearl and Cordingly 1975). On level grounds, the operation is fairly easy and effective. On undulating sites, soil conservation measures are essential before reseeding.

Reseeding can be done normally to ensure good stand, if reseeding is done after monsoon sets in, but sometimes dry sowings before monsoon can also be done. After sowing, soil is given with a light harrowing. The grazing during first year of reseeding should be very light and allowed only after the grass has set seed. From the second year onward, moderate grazing can be allowed.

(e) Conservation of Soil and Moisture
The proper conservation of both water and soil is an integral part of all good grassland management systems. When properly grazed, eroding forces are kept in check and the grassland is in balance with erosive factors and no special conservation measure could be needed, but when grasslands have been mismanaged by neglect and overgrazing for many years, soil and water conservation measures become essential for any improvement plan. On degraded grassland, especially on sloppy ground, the first measure of improvement could be to prevent any further erosion of the soil. Where the erosion has already progressed to the stage of gully formation, dams will have to be put across the gully channels. A number of small check dams are more effective than a few large ones. Terraces or surges are useful in high rainfall regions in directing water from the slopes to channels with a minimum of soil loss from the grasslands. Erosion can be controlled by avoiding excessive removal of herbage and adopting contour bunding for soil as well as moisture conservation.

(f) Rotational Stocking
Rotational stocking, also called rotational grazing, is the grazing of two or more subdivisions of the pasture, called paddocks, in sequence followed by a rest period for the recovery and regrowth of the paddock. The major difference between continuous and rotational stocking is that the grazier, and not the

livestock, is controlling the length of the rest period. Advantages of rotational stocking may include improved pasture longevity, more timely utilization of forage, opportunities to conserve surplus forage, increased stocking rate (generally 15–30%), more uniform distribution of excreta by the animals, and better animal management.

The main decisions that the grazier must make when using rotational stocking are the length of the rest period between grazing and the length of time that the livestock will be on one paddock (called the grazing period). With this information, the approximate number of paddocks needed can be calculated. For example, if the grazier wants a pasture rest period of approximately 28 days and a grazing period of 7 days per paddock, five paddocks will be needed. If a rest period of 20 days and a grazing period of 1 day are desirable, then 21 paddocks will be needed. A simple formula to calculate the number of paddocks needed is the sum of length of grazing period and length of rest period divided by the length of the grazing period. Many graziers will vary the length of the rest period with season of the year.

(g) Intensity of Grazing
Intensity of grazing is the term pertaining to the amount of the forage mass removed or grazed from a pasture during the grazing period. Grazing should start in a paddock when vegetation is about 8 inches high for tall growing species and 5 to 6 inches high for short growing plants. Animals should be removed when the forage height is reduced to 2–3 inches. Move the animals rapidly through all the pastures to establish a staggered forage regrowth pattern necessary for the rest of the grazing season. Delay grazing until the soils are dry enough to support the weight of the animals without punching.

(h) Duration of Grazing
The length of time that animals have access to an individual paddock is referred to as the residency period. The residency period should be as short as possible to prevent animals from grazing regrowth. Plant regrowth may begin in 3 to 4 days in May and June but may not begin for a week or longer during July and August when the weather is hot and dry. The more often livestock are moved to fresh grass, the more uniform the quality and quantity offered. Lactating dairy cows should be provided with a fresh paddock after each milking for optimum milk production but could stay in one paddock for up to 3 days. Beef cattle, heifers, dry cows, and other animals can graze on a single paddock for 3 to 4 days, but no longer than 6 or 7.

(i) Resting or Recovery Period
The interval of time a pasture is allowed to regrow after grazing is the resting or recovery period. This resting period is crucial for high forage production from pastures. The frequency at which a pasture is grazed controls the quality and quantity of feed that is produced. Resting or recovery period will vary with the seasons. Pastures should be grazed as often as every 10 to 15 days in the spring, 15 to 20 days in late spring and early summer, and 25 to 30 days during summer and fall.

(j) Carrying Capacity

Expressed in animal unit months, carrying capacity reflects forage productivity and pasture size. It is the pasture's ability to produce forage to meet the requirements of grazing animals.

Carrying capacity is the stocking rate that is economically and environmentally sustainable for a particular grazing unit throughout the grazing season. Carrying capacity is largely determined by four factors: (1) annual forage production, (2) seasonal utilization rate, (3) average daily intake, and (4) length of the grazing season. These terms can be expressed in the mathematical formula below:

$$\text{Carrying capacity} = \frac{\text{Annual forage production} \times \text{Utilization rate}}{\text{Annual daily intake} \times \text{Length of grazing season}}$$

Annual production of forage is the total quantity of dry forage produced annually per acre. The rate of use is the percentage of annual forage production that the grazing cattle actually harvest.

(k) Stocking Rate

It is the number of animals on a pasture during a month or grazing season and is usually expressed in animal unit months per unit area. Using a stocking rate too high for the land to support over a period of time can result in overgrazing.

(l) Live Fencing System

Live fences are single or multiple rows of trees or shrubs that form a barrier along the border. Kangayam tract is unique in India because private pastureland protects the grasses of *Cenchrus ciliaris* and *Cenchrus setigerus* interspersed with trees of *Acacia leucophloea*. The grazing area in Erode and Karur districts under paddock system of management has been estimated to be 1247 sq.km.

2.8 Opportunities/Future Scopes for Improvement of Pasture Resources

Despite various constraints on the productivity of pastures and grasslands, the development of grazing areas and fodder cultivation has tremendous potential in India.

Studies conducted at Indian Grassland and Fodder Research Institute, Jhansi, have revealed that the initial protection from grazing of newly improved grasslands can lead to better establishment and higher biomass (3.31 Mg ha^{-1} against 0.93 Mg ha^{-1} without protection). They added that live-hedge fencing has been found to be economical and suitable. Extensive grazing studies have revealed that the appropriate stocking rates are 25 to 30, 20, 17, 12, and 6 ACU per 100 ha for the management of excellent, good, fair, poor, and very poor classes of rangelands, respectively. Further, basic moisture conservation techniques like contour furrowing, contour bunding, and contour trenching can lead to increases in herbage yield. Studies undertaken on natural pastures dominated by *Sehima nervosum*, *Heteropogon contortus*, and *Iseilema laxum* have revealed that their production can be increased from 4.1 to 7.6, from 3.4 to 5.6, and from 4.5 to 6.4 Mg ha^{-1} per year by the application of nitrogen at a rate of 40 kgha^{-1}(Shankar and Gupta 1992). Further, in a silvopastoral systems on degraded grazing lands, Pathak and Roy (1995) enhanced biomass by up to 7 to15 Mg ha^{-1} per year. Misri (1986) also reported an additional herbage availability of 35 to 48 Mg ha^{-1} under fruit-based silvopasture systems. Some of the thrust areas of work in this field may be as follows:

- Forage production must be taken up as a first management goal, and 25% of the forest area should be put under trees with regulated accessibility to the farmers.
- Growing forage grasses and fodder trees along village roads and panchayat lands.
- Growing forage grasses and fodder trees on terrace risers/bunds – a noncompetitive land use system.
- Conservation of native biodiversity for future improvement.
- Breeding biotic, abiotic, stress-tolerant cultivars of forage species suitable for area not used under arable agriculture.
- Participatory techniques to be adopted to identify the problems and to carry out the improvement program.
- In-depth studies on migratory graziers.
- Forage-based agroforestry systems.
- Controlled grazing to maintain the productivity of pasture (grazing should be allowed as per carrying capacity).

2.9 Conclusions

Grazing management is an important tool for efficient utilization of the pasture resources. Appropriate choices of stocking rate or height of grazing (how close) and rotational or continuous stocking (how often) are critical to the success of a grazing system. The best management practices match the nutritional requirements of the animal with the ability of the pasture to meet these needs. This can be done through choice of species and by choice of grazing management. Human population explosion places great demands on the earth's natural resources. Large stretches of land such as forests, grasslands, and wetlands have been converted into intensive agriculture. Land has been taken for industry and urban development. These changes in the land use patterns and rapid disappearance of favorable natural ecosystems have put great pressure on animal agriculture also.

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3 The Influence of Overmature, Degraded *Nothofagus* Forests with Strong Anthropic Disturbance on the Quality of an Andisol and its Gradual Recovery with Silvopasture in Southwestern South America

Marianela Alfaro, Francis Dube, and Erick Zagal

Abstract

The increasing demand for timber and non-timber products from native forests in Chile and the cattle grazing has augmented the rate of degradation of these ecosystems. This process results in the need to know which of the dynamic variables are involved in its regulation. Soil quality indicators like soil organic carbon (SOC), soil microbial respiration (SMR), microbial biomass carbon (MBC), potential net N mineralization (N-min), and nitrification (N-NO_3), soil aggregates, and light fraction (LF) were evaluated at two different depths of the soil in *Nothofagus obliqua* (deciduous) and mixed *N. dombeyi*-*N. obliqua* (evergreen-deciduous) forests, where a 30-ha silvopastoral trial was established, after this evaluation, in early 2016. The SOC, SMR, MBC, N-min, and N-NO_3 were significantly higher in the *N. obliqua* forest than the mixed forest, 8%, 17%, 17%, 40%, and 20%, respectively ($p < 0.05$). The dry weight in soil fractions did not present differences between forest types. C and N contents in the LF (labile, undecomposed organic matter of plant origin) were higher in the deciduous forest, 9% and 20%, respectively ($p < 0.05$). Our results suggest that soil quality was favored by the quality of organic matter in the site dominated by deciduous species, which translates into more favorable conditions for the activity of

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microorganisms, nitrogen dynamic, and C and N content in the light faction. The intrinsic characteristics of the plant residues associated with higher rates of decomposition can stimulate the activity of the biota and especially the soil microorganisms, which would lead to higher values of the different indicators evaluated. This novel silvopastoral system will likely help restore the most degraded sites through improvement of the soil quality. This kind of information allows obtaining knowledge of the forest areas and their sustainability, mainly for the planning of long-term, durable silvopastoral practices.

Keywords

Forest degradation · *Nothofagus obliqua* · *N. dombeyi* · Silvopastoral systems · Temperate forest · Volcanic soil

3.1 Introduction

The soils of south-central Chile have been created by a high volcanic activity (Stolpe and Undurraga 2016). This area of the Chilean Andes is characterized by temperate forests dominated by several species of the genus *Nothofagus* that have undergone major changes in their distribution area due to human action, which has mainly affected soil properties, such as reduced fertility and quality (Altamirano and Lara 2010).

The remaining forests correspond to a secondary succession, as they originate in partially disturbed areas, due to logging and grazing, sediment trapping, and forest fires (Bergh and Promis 2011). Therefore, to know the dynamics of soil quality, this type of ecosystem, with different plant communities, would allow to obtain knowledge in the forest areas that still remain (Lara et al. 2009). Soil quality evaluation is very useful for determining the sustainability of soil use and management systems. The concept of soil quality is based on its multifunctionality. It is defined as the ability to function as part of an ecosystem (natural or anthropogenic) and maintain plant and animal productivity (Bastida et al. 2008; Zagal et al. 2009).

Soil organic matter (SOM) is a key soil quality attribute because it has far-reaching effects on physical, chemical, and biological properties; however, high SOM levels and the natural variability of soil make it difficult to measure the effect of short-term changes in soil use (Zagal et al. 2009). Decker and Boerner (2003) demonstrated that soil N transformation rates, pH, and plant available phosphorus supplies do differ among stands occupied by different *Nothofagus* species and have also shown that organic matter quality varies more among these forest stands than does organic matter quantity.

The labile SOM fractions (incompletely transformed animal, plant, and microorganism residues) tend to be more sensitive to changes in soil management practices or environmental conditions than total SOM; they are therefore, well established as early indicators of soil quality and use change (Bastida et al. 2008). These indicators include the microbial biomass C, microbial respiration rate, nitrogen dynamics, particulate organic matter (POM), light fraction (LF), and soil carbon (C) and nitrogen (N) content in the fractions (Bastida et al. 2008; Zagal et al. 2009). The microbial activity of the soil constitutes a measure of ecological importance; on the one hand, it represents the level of the biological activity of the labile component of the OM of the soil, and on the other hand, it integrates the factors of the environment and its influence on the biogeochemical cycles (Zagal et al. 2009).

SOM can be fractionated according to its lability (relative ease with which it is decomposed by soil microorganisms) (Dube et al. 2009). The fraction with higher lability is used as an indicator of sustainable management because its soil content changes in the short term (several months to years) depending on the vegetation, management, and addition of vegetal residues and their decomposition in the soil (Dube and Stolpe 2016). This fraction has been designated as macroaggregates (>212 μm in diameter). The intermediate fraction has less lability and is associated with the mesoaggregates (212–53 μm in diameter), and the heavy fraction is more stable and associated with the microaggregates (<53 μm in diameter) (Dube et al. 2009). The light fraction is considered as plant and animal residues to be decomposed more rapidly, not firmly associated with soil minerals; it contributes up to 30% of total SOM and is an important pool of C availability during decomposition (Zagal et al. 2009).

Although abiotic conditions have traditionally been interpreted as the regulators of vegetation composition, biotic interactions, particularly in the soil, they are also reported as one of the major factors in the composition of plant communities (Perez et al. 2009). In Chile, there are few biological and biochemical studies of soil in forested communities in the south-central Andean zone. This is an important weakness because it is a sensitive indicator of changes in land use, considering the new challenges of sustainable management of renewable resources in this area (Lara et al. 2009; Perez et al. 2009; Rivas et al. 2009). A better understanding of different soil quality indicators allows an integrated assessment of the ecosystem. This is due to the crucial role of several biological and biochemical activities in the soil, their ease of measurement, and their rapid response to changes in land use and management (Perez et al. 2009; Zagal et al. 2009). It is postulated that the plant communities-soil interactions will determine the quality of the soil and the activity of its microbial processes, in forest with anthropic disturbance. The objective of this study was to evaluate soil quality in two plant communities (deciduous and mixed perennial-deciduous) of old Andean *Nothofagus* forests in south-central Chile, to plan silvopastoral management to be implemented.

3.2 Site Descriptions and Characterization

The study site is located at the "Ranchillo Alto," commune of Yungay, Biobío Region, Chile (37°04' S and 71°39' W) (Figs. 3.1 and 3.2), which covers approximately 653 ha. The prominent climate is warm temperate Mediterranean with a short dry season (<4 months), with an average annual rainfall of 3000 mm and a mean annual temperature of 13.5 °C (Rivas et al. 2009). The site is located on volcanic soil

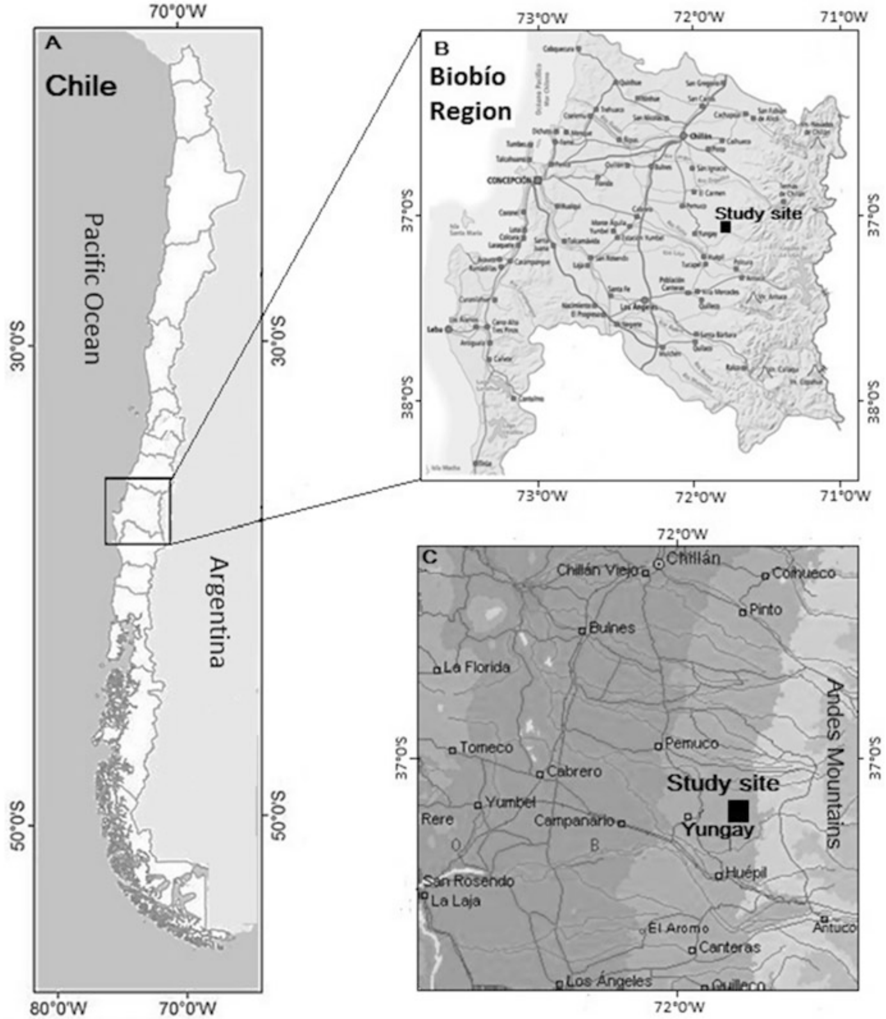

Fig. 3.1 Location of the study site. Map of Chile (**a**); Biobío Region (**b**); location of the "Ranchillo Alto" property (black square) near the town of Yungay (**c**)

(Andisol) that has been classified as Haploxerands (CIREN, 1999); they are characterized by low bulk density (<0.9 g cm^{-3}) and high organic matter content.

The Ranchillo Alto property includes a large area of native forest, which has been under heavy pressure from long-term and ongoing land uses that include cattle grazing and tree cutting for firewood, charcoal, and timber. These processes strongly threaten overall biodiversity, soil quality, and the existence of the forest itself (Dube et al. 2016). Livestock raising is a common activity throughout the property, except for the areas with higher elevations and peaks. Intensive and illegal logging could be

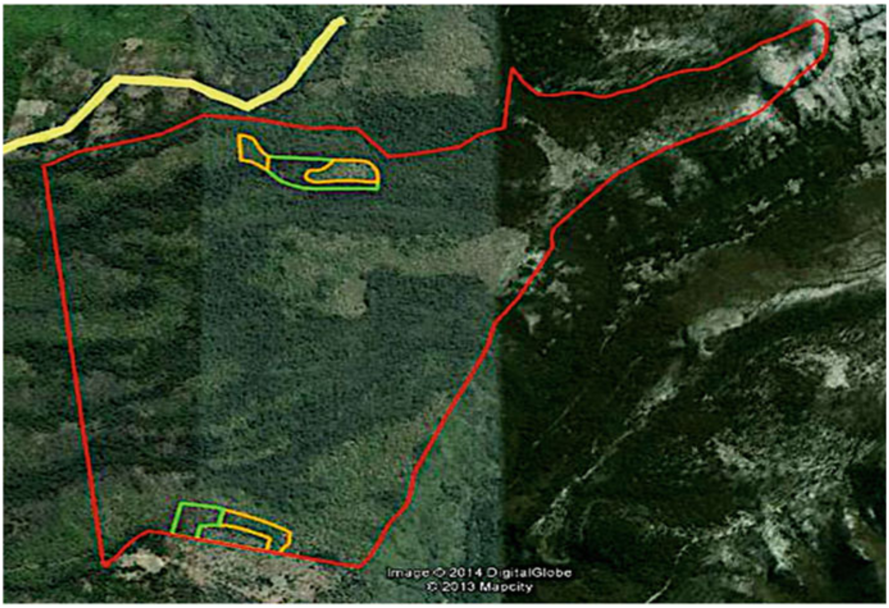

Fig. 3.2 Satellite photograph of the "Ranchillo Alto" property, Chile, showing the location of the partly closed canopy treatments (green lines within black circles) (north site at 1.300 m altitude, Lat 37°03′30.86" S, and Long 71°38′50.60" W; south site at 1.250 m altitude, Lat 37°04′52.10" S, and Long 71°39′12.39" W (map by Google Earth 2014)

found throughout the site, and a large proportion of the forest has already been altered and subsequently degraded. Obvious signs of degradation can easily be seen in the plant communities of *Nothofagus obliqua* (Mirb.) Oerst. and mixed forest of *Nothofagus dombeyi* (Mirb.) Oerst.-*Nothofagus obliqua*, where continuous, nonsystemic grazing was used (Dube et al. 2016). In May 2016, after the evaluation of the soil, a silvopastoral system with improved grassland was implemented (Figs. 3.3 and 3.4). The forage species that were sown include *Lolium multiflorum* var. *westerwoldicum* (4 kg ha^{-1}), *Phalaris aquatica* (2 kg ha^{-1}), *Lolium perenne*, *Festuca arundinacea* and *Dactylis glomerata* (15 kg ha^{-1}), and *Trifolium incarnatum*, *T. subterraneum*, and *T. vesiculosum* (6 kg ha^{-1}). Application of NPK fertilizer (150–200-100) included Supernitro (100 kg ha^{-1}), Triple Superphosphate (88 kg ha^{-1}), and Muriate of potash (25 kg ha^{-1}).

3.3 Experimental Design and Methods

The tree cover level was evaluated in January 2015, using a Solariscope (SOL300, Behling, Berlin, Germany) that was placed at 1.5 m height above the ground (Fig. 3.5). Evaluations were done every 20 m in two parallel transects (1000 m

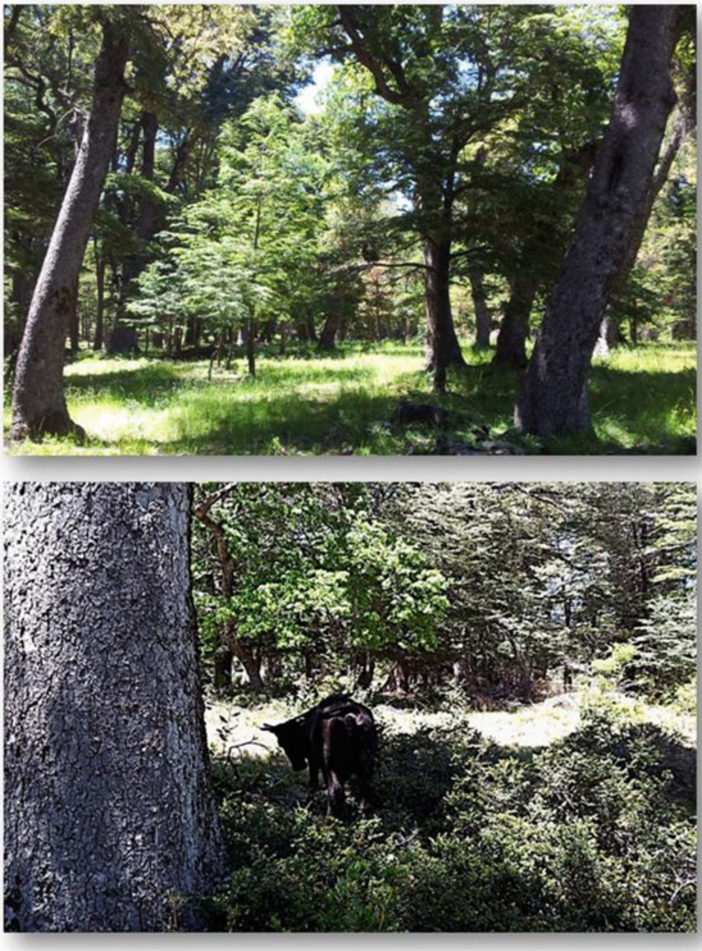

Fig. 3.3 Silvopastoral site in northern *Nothofagus dombeyi-N. obliqua* mixed forest area with beef cattle being continuously grazed under partly closed tree coverage (45–55% luminosity) after establishment of improved pasture in Ranchillo Alto (1300 m above sea level) (Photos taken in October 2017, Francis Dube)

length, 50 m spacing) with east-west orientation (Dube and Stolpe 2016). The level of tree cover determined was partly closed (Table 3.1). For soil sampling, a randomized complete design with three replicates (plots) randomly distributed was established. All plots had a size of 50 × 50 m following the recommendations of Donoso et al. (1984), a slope ranging from 10 to 15%, and a uniform aspect and were located at similar altitude (Table 3.1).

Fig. 3.4 Silvopastoral site in southern *Nothofagus obliqua* forest area with beef cattle being continuously grazed under partly closed tree coverage (45–55% luminosity) after establishment of improved pasture in Ranchillo Alto (1250 m above sea level) (Photos taken in October 2017, Francis Dube)

Soil sampling was done in November 2015. In each plot, soil samples were taken, composed of eight random subsamples at depths of 0–5 and 5–20 cm, following the recommendations of Dube et al. (2009). The samples were placed in polyethylene bags, were taken to the laboratory and were frozen at −7 °C, then were unfrozen, air-dried and sieved using stainless steel sieve having 2 mm apertures, and stored at 4 °C for the analysis described below.

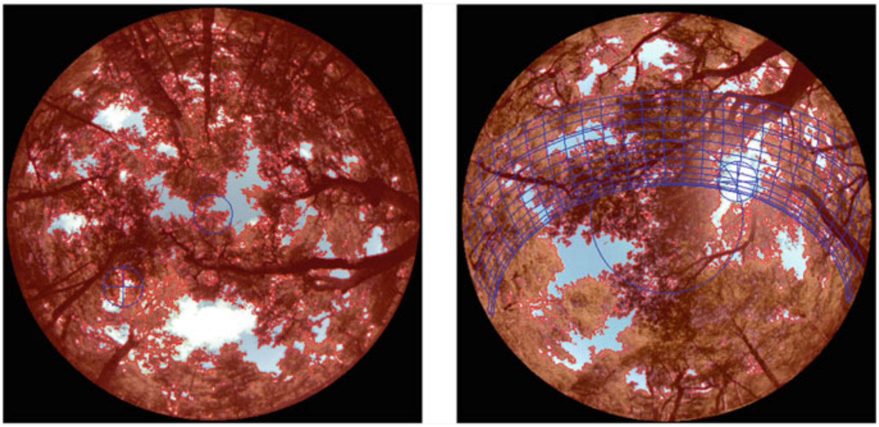

Fig. 3.5 Hemispherical snapshots of the partly closed canopy treatments (north site (**a**) with mixed *Nothofagus dombeyi* and *N. obliqua* and south site (**b**) with *N. obliqua* only) using a Solariscope SOL300 (Behling, Germany) (Photos taken at the "Ranchillo Alto" property in January 2015, Francis Dube)

3.3.1 Chemical and Biological Parameters for Analysis of Soil Quality

The soil organic carbon was measured by dry combustion (Wright and Bailey 2001). Soil pH was measured using a 1:2.5 mixture of soil and water (Sadzawka et al. 2006).

Soil microbial respiration (SMR) and microbial biomass C (MBC) were performed following the SIR method (substrate-induced respiration) described by Anderson and Domsch (1978). Three subsamples of 10 g dry soil for each soil sample were incubated to 22 °C for 24 hours and then placed in a gas-tight container suitable for CO_2 headspace analysis. A concentration series of glucose amendments in liquid form (Horwath and Paul 1994) to bring slightly dried soil to 60% WFPS (water-filled pore space) (Linn and Doran 1984) were added. The CO_2 content was analyzed using a CO_2 analyzer (LI-COR LI-820, Lincoln, USA). The minimum concentration of glucose giving maximal respiratory response was added to replicate subsamples of soil. In our case, we used 5 and 10 μMole g^{-1} dry soil for 0–5 cm and 5–20 cm depths, respectively. MBC was calculated using Eq. (3.1) (Anderson and Domsch 1978):

$$x = 40.4y + 0.37 \tag{3.1}$$

where x is the total microbial biomass C (μg C g^{-1} dry soil) and y is the maximum initial rate of CO_2 respiration (ml CO_2 g^{-1} dry soil).

Table 3.1 Treatment descriptions and baseline information about the study site that was established in the Ranchillo Alto state-owned property, Chile

Treatment	Plot size (m)	Tree cover condition	Tree cover description	Altitude	Species	Stocking density (stems ha^{-1})	Mean DBH (cm)	Basal area ($m^2\ ha^{-1}$)	Mean HT (m)
T1	50 × 50	Partly closed (PC)	Ground with 45–55% of external light (average Of area)	1300 m	*N. dombeyi* *N. obliqua* *Festuca* sp., *Gaultheria phillyreifolia* *Rosa rubiginosa*	168[a]	66.5 *N. dombeyi*, 64.3 *N. obliqua*	57.4[a]	25.0
T2	50 × 50	Partly closed (PC)	Ground with 45–55% of external light (average Of area)	1250 m	*N. obliqua*, *Festuca* sp., *Gaultheria phillyreifolia* *Rosa rubiginosa*	258	32	20.7	20.0

[a]Values added between those of Coigüe (*N. dombeyi*) and Roble (*N. obliqua*). DBH: diameter at breast height, HT: total height

3.3.2 Potential Net N Mineralization (N-Min) and Nitrification ($N\text{-}NO_3$)

Three subsamples of 5 g dry soil were used as control, and three additional subsamples were incubated at 22 °C for 10 days at 60% WFPS (Linn and Doran 1984), then put in a 150-ml plastic flask with 25 ml of K_2SO_4 (0.5 M) solution, and were shaken for 1 h at 180 rev·min^{-1}. The extract was decanted, filtered, and analyzed by colorimetry using a UV-visible spectrophotometer (AA3, BRAN +LUEBBE, Norderstedt, Germany). Nessler reagent and sulfosalicylic reagent were used to determine the N-mineral as ammonium and nitrate (Alef 1995). N-min and $N\text{-}NO_3$ were calculated using Eqs. (3.2) and (3.3) (Trap et al. 2009):

$$\mathrm{Nmin} = \left[\left(\mathrm{N-NH_4^+} + \mathrm{N-NO_3^-}\right)_f - \left(\mathrm{N-NH_4^+} + \mathrm{N-NO_3^-}\right)_i\right]/\mathrm{T_d} \quad (3.2)$$

$$\mathrm{N-NO_3^-} = \left[\left(\mathrm{N-NO_3^-}\right)_f - \left(\mathrm{N-NO_3^-}\right)_i\right]/\mathrm{T_d} \quad (3.3)$$

where the subscripts i and f indicate concentrations measured before and after aerobic incubation, respectively, and Td indicates incubation time in days. N-min and $N\text{-}NO_3$ were expressed as μg Ng^{-1} dry soilday^{-1} (μg Ng^{-1} dry soild^{-1}).

3.3.3 Physical Fractionation of Soil Organic Matter

The SOM fractionation analysis was performed following the method described by Feller et al. (1991). The light, intermediate, and heavy fractions of SOM were separated as follows: 50 g of soil was mechanically dispersed in a plastic bottle (250 ml) containing ten glass beads (6 mm diameter) and 180 ml of distilled water and shaken at 50 cycles·min^{-1} for 16 h using an overhead shaker (Hie-MIX Reax 2, Heidolph, Germany). The disrupted soil aggregates were then wet sieved using stainless steel sieves having 212 and 53 μm apertures. The light fraction of organic matter and sand (which were retained on the 212 μm sieve) were separated by flotation and sedimentation in distilled water. Soil samples were sieved accordingly to separate the following fractions: macroaggregates (>212 μm), mesoaggregates (212–53 μm), and microaggregates (<53 μm) (Dube et al. 2009). The fractions were dried at 50 °C for 48 h and weighed. The C and N contents of the light, intermediate, and heavy fractions were then measured by dry combustion (Wright and Bailey 2001).

3.3.4 Statistical Analyses

Two-way ANOVA was used to evaluate the effects of plant community ($n = 2$) and soil depth ($n = 2$) on the dependent variables SOC, C/N, pH, SMR, MBC, N-min, and $N\text{-}NO_3$ ($P < 0.05$). Three-way ANOVA was used to evaluate the effects of plant community ($n = 2$), soil depth ($n = 2$), and soil fraction ($n = 4$) on the dependent variables dry weight and organic C and N content in the soil fractions. Normality (Kolmogorov-Smirnov test) and homoscedasticity of variance (Levene's test) were evaluated prior to analysis. Logarithmic transformations were performed when these assumptions were not met (N-min, N-NO_3). Student's *t*-test ($P < 0.05$) was used for the comparison of means with a significance level of 95%. Statistical analysis was performed with the program R Project for Statistical Computing (version 3.2.5, R Foundation for Statistical Computing, Vienna, Austria).

3.4 Key Findings and Discussion

The forest type and soil depth had significant effect on the SOC, N, pH, SMR, MBC, N-min, and N-NO_3 variables (Table 3.2). The analysis showed no significant interaction for forest type × soil depth ($p < 0.05$), for all of the previous parameters.

According to Table 3.3, the SOC was 10% significantly higher in the *N. obliqua* forest than the mixed forest, at 0–5 cm soil depth. The pH in both systems was moderately acidic, characteristic in soil with higher SOC, and was lower at the 0–5 cm than 5–20 cm soil depth; soil layers with higher OM tend to be more acidic (Potthast et al. 2017). SMR, MBC, N-min, and N-NO_3, at 0–5 cm soil depth, only were significantly higher in the *N. obliqua* forest than in the mixed forest. SMR and MBC were 17% higher in the *N. obliqua* forest, N-min was 40% higher, and N-NO_3 was 20% higher. The 0–5 cm soil depth presented the highest values of all parameters.

SOC, SMR, MBC, N-min, and N-NO_3 were sensitive at the forest type; the highest values of these parameters were associated to the *N. obliqua* forest. Zagal et al. (2009) mention that the higher contents of SOC are associated with greater microbial activity; this coincides with our results, where SMR and MBC were higher at higher SOC. The accumulation of OM would tend to increase microbial activity, since the product of degradation of the plant material facilitates the entry of C and N into the system, which serves as an energy source, especially for those microorganisms and enzymes related to the cycles of C and N (Alvear et al. 2007a).

The forest type did not show any effect on the C/N ratio. Rivas et al. (2007), however, found that the litter under the *N. obliqua* forest had a better C/N ratio, which favors the rate of decomposition in relation to the evergreen forest, what he attributed to the higher contents lignin of the residues from the evergreen forest, which slow down the decomposition and release of nutrients.

The tendency presented by our data is that higher SOC was recorded at the 0–5 cm soil depth; SOC is usually closely related to larger OM content accumulated in the upper layer of the soil. Dube et al. (2009), who studied a *Nothofagus pumilio* forest in Chilean Patagonia, indicate that superficial OM was less resistant to microbial decomposition than OM in lower soil layers; therefore, the contents of SOC are higher.

The results indicated higher values of SMR and MBC in the *N. obliqua* forest, indicating a greater microbial activity in this forest type. This may be related to differences between the residues that enter in the soil, from the *N. obliqua* forest and

Table 3.2 *p* value for forest type and soil depth and their interaction for the chemical, biochemical, and biological parameters. Measurements were taken in Ranchillo Alto, Chile, November 2015

	p value						
Source of variation	SOC	C/N	pH	SMR	MBC	N-min	$N\text{-}NO_3$
Forest type	**0.0005**	0.28	**0.002**	**0.001**	**0.001**	**0.001**	< **0.0001**
Soil depth	< **0.0001**	0.22	**0.003**	< **0.0001**	< **0.0001**	< **0.0001**	< **0.0001**
Type × depth	0.96	0.50	0.07	0.13	0.12	0.13	0.08

Bold values are significant. SOC: soil organic C, C/N: carbon-nitrogen ratio, SMR: Soil microbial respiration, MBC: Microbial biomass C, N-min: Potential net N mineralization and $N\text{-}NO_3$: Potential net nitrification.

Table 3.3 Means (± standard error) for soil organic carbon, pH, soil microbial respiration, microbial biomass C, and potential net N mineralization and nitrification. Measurements were taken in Ranchillo Alto, Chile, November 2015

Variable	Forest type	Depth 0–20 cm	0–5 cm	5–20 cm
SOC (%)	*N. obliqua*	8.22 ± 0.15 a	9.21 ± 0.13 a A	6.94 ± 0.13 a B
	Mixed	7.19 ± 0.15 b	8.32 ± 0.13 b A	6.44 ± 0.13 a B
pH (H_2O)	*N. obliqua*	6.13 ± 0.08 a	6.03 ± 0.08 a A	6.52 ± 0.08 a B
	Mixed	6.14 ± 0.08 a	6.24 ± 0.08 a A	6.65 ± 0.08 a B
SMR (μg $CO_2 \cdot g^{-1}$ dry soil)	*N. obliqua*	69.22 ± 2.32 a	81.45 ± 2.21 a A	47.81 ± 2.21 a B
	Mixed	52.12 ± 2.32 b	66.58 ± 2.21 b A	40.40 ± 2.21 a B
MBC (μg $C \cdot g^{-}$ dry soil)	*N. obliqua*	1255.26 ± 35.46 a	1774.15 ± 47.95 a A	1042.98 ± 47.95 a B
	Mixed	922.82 ± 35.46 b	1450.95 ± 47.95 b A	881.76 ± 47.95 a B
N-min (μg $N \cdot g^{-1}$ dry soil$\cdot d^{-1}$)	*N. obliqua*	1.12 ± 0.10 a	1.67 ± 0.10 a A	0.48 ± 0.10 a B
	Mixed	0.85 ± 0.10 b	1.01 ± 0.10 b A	0.20 ± 0.10 a B
N-NO_3 (μg N-$NO_3 \cdot g^{-1}$ dry soil$\cdot d^{-1}$)	*N. obliqua*	0.32 ± 0.05 a	0.46 ± 0.06 a A	0.27 ± 0.06 a B
	Mixed	0.24 ± 0.05 b	0.37 ± 0.06 b A	0.16 ± 0.06 a B

SOC: soil organic carbon, SMR: soil microbial respiration, MBC: microbial biomass C, N-min: Potential net N mineralization, N-NO_3 Potential net nitrification. Values with the same lowercase letter within a column are not significantly different according to student's *t*-test ($p < 0.05$). Values with the same uppercase letter within the 0–5 and 5–20 cm soil depths and a same treatment are not significantly different according to student's *t*-test ($p < 0.05$).

the mixed forest, the latter dominated by the perennial species of *N. dombeyi*. Staelens (2011) in a study of nutrient dynamics in four Valdivian rainforests mention that in evergreen forest, the quantitative and qualitative characteristics of the leaf litter and its rate of decomposition may restrict the activity of the biota and especially the soil microorganisms. Wang et al. (2017) indicate that soil biota is influenced by the quality and quantity of plant material provided to the soil and climatic characteristics that also affect microbial abundance, the involved species, and its trophic composition.

The results obtained for SOC, SMR, and MBC for *N. obliqua* forest are very similar to values reported by Alfaro et al. (2018) in a study in disturbed *Nothofagus* forest under different tree covers in south-central Chile. Otherwise, the results obtained for MBC for both forest type are very similar to values reported by Alvear et al. (2007b) for the spring season in a *N. obliqua* forest with approximately 78% of tree cover. The values are higher than those found by Lillo et al. (2011) for *N. alpina* -*N. dombeyi* tree community in southern Chile. The results for SMR and MBC are lower than the values recorded by Dube et al. (2009) in a secondary *N. pumilio* forest in the Chilean Patagonia. The differences can be attributable to the different quality (chemical and physical leaf composition between deciduous and perennial trees), distribution of available substrates in different ecosystems, and different methods for analysis (Dube et al. 2009).

The higher microbial activity in the *N. obliqua* forest was associated with higher rates of N-min and N-NO_3. In this sense, Alvear et al. (2007) indicate that the microbial biomass activity facilitates the decomposition and mineralization processes of the OM deposited in the soil surface, when the humidity conditions exist for this, which generates more amount of substrates and nitrogen compounds. The N-min and N-NO_3 values that we determined (Table 3.3) concurred with the annual ranges reported by Rivas et al. (2009) (−3.47 to 7.98 μg N g^{-1} dry soild^{-1} and -2.6 to 3.75 μg N-NO_3 g^{-1} dry soild^{-1}), who presented higher rates in summer and autumn at the 0–10 cm depth in a secondary *N. obliqua* forest in south-central Chile. The results also coincided with those found by Perez et al. (2009) for evergreen forest in Chiloé, Chile, with maximum rates of N-min of 6.00 μg N g^{-1} dry soild^{-1} in field and laboratory incubations; they also indicated that N-NO_3 was approximately 50% of total N-min; our results for deciduous forest indicate that N-NO_3 was 45% of total N-min and 30% for mixed forest. Positive N-min rates indicate that N is potentially available for the consumption of plants and soil microorganisms (Pérez et al. 2009).

The highest N-min rate of the *N. obliqua* forest compared to the mixed forest could be attributed to the difference in litter quality (variable not measured in this study). Decker and Boerner (2003) in a study about the influence of the elevation and vegetation on soil properties in Chilean *Nothofagus* forests mention that the net N in evergreen leaf litter decreased during decomposition and increased in the deciduous leaf litter, because the deciduous (angiosperm) litter presents relatively low lignin content and C:N ratio and the evergreen (gymnosperm) litter, with high lignin content and C:N ratio, reduces decomposition. These authors also found that mean lignin/N in litter of *N. obliqua* and *N. dombeyi* was 21.7 (SE = 3.6) and 27.5 (SE = 3.6), respectively. Although these litter lignin/N ratios do not significantly differ, they do illustrate a similar pattern to the nitrification rates reported. Hevia et al. (1999) found foliar N to be lowest in *N. dombeyi* leaves and highest in *N. obliqua* leaves. These same authors found that the reabsorption of nitrogen from the leaves by the soil did not differ between these species, so the differences in the concentrations of N in the soil were transferred to the litter. Finally, Decker and Boerner (2003) mention that the long-term effect of deposition and decomposition of deciduous versus evergreen litters may further affect both the chemical and biological characteristics of the soils under those trees in such a manner as to produce an environment under evergreens that is less conducive to decay and nutrient mineralization than that under deciduous species.

The soil fraction had a significant effect on the dry weight of the soil fractions; forest type and soil depth did not have significant effect on the same variable, significant interaction between forest type × fraction and soil depth × fraction were also observed (Table 3.4). Otherwise, the forest type, soil depth, and soil fraction had a significant effect on the organic C and N content in the soil fractions. Organic C content presented significant interaction between forest type × fraction and soil depth × fraction. N content presented significant interaction between forest type × fractions only ($p < 0.05$).

Table 3.4 *p* value for the forest type, soil depth, and soil fraction factors, and their interactions, for the variables dry weight of the soil fractions and organic C and N contents in the soil fractions. Measurements were taken in Ranchillo Alto, Chile, November 2015

	p value		
Source of variation	Dry weight of soil fractions	Organic C content (SOC)	N content
Forest type	0.35	<**0.0001**	<**0.0001**
Soil depth	0.84	<**0.0001**	<**0.0001**
Soil fraction	<**0.0001**	<**0.0001**	<**0.0001**
Forest type × depth	0.98	0.19	0.86
Forest type × fraction	**0.002**	**0.008**	<**0.0001**
Depth × fraction	<**0.0001**	<**0.0001**	0.80
Forest type × depth × fraction	0.06	0.65	0.84

Bold values are significant

The result indicated that the dry weight in the soil fractions was sensitive to the distribution by fraction and was dominated by the microaggregates, followed by mesoaggregates, macroaggregates, and finally the LF; this is consistent with the results presented by Dube and Stolpe (2016) in a study of different degradation levels in *N. obliqua* forest in the Andean and coastal zones of south-central Chile and Dube et al. (2009) for a secondary *N. pumilio* forest in Patagonia. Our results are also consistent with the results found by Alfaro et al. (2018) in a study in disturbed *Nothofagus* forest under different tree covers.

The dry weight in all soil fractions did not present differences between forest types; however, the higher C and N contents in the LF (labile OM) present in the deciduous forest lead us to think that the quality of the organic matter of the residues that enter the systems possibly varies much more than the residue amount; this is consistent with the results presented by Decker and Boerner (2003). Zagal et al. (2009) mention the importance of the LF as substrate for soil microbes and as a source of soil nutrients; the higher C and N contents in the LF in the deciduous forest probably favored the higher amount of SOC, microbial activity, N-min, and N-NO_3. The forest type and soil depth did not have significant effect on the dry weight of the soil fractions (Fig. 3.6a, b). The dry weight of the soil fractions was sensitive to the distribution by fraction and was dominated by the microaggregates, followed by mesoaggregates, macroaggregates, and finally the LF (Fig. 3.6a).

The relative dry weight of the LF fraction and macroaggregates (labile OM), according to forest type × fraction interaction, did not present significant difference between forest types (Fig. 3.6a). The same trend was observed for the soil depth × fraction interaction (Fig. 3.6b).

Contrast analysis for the interactions indicated that C and N contents in LF were significantly higher in the *N. obliqua* forest, 9% and 20%, respectively (Fig. 3.6c, e). C and N content were significantly higher in the LF fraction, followed by mesoaggregates, microaggregates, and finally macroaggregates, for both soil depths

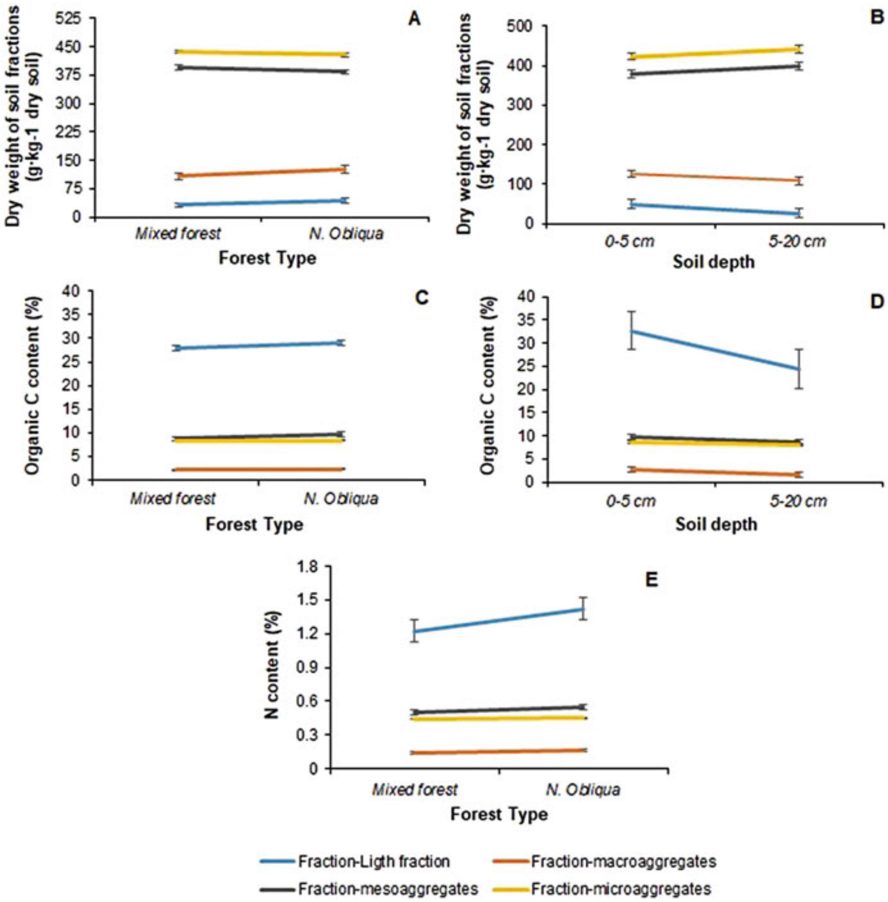

Fig. 3.6 Dry weight of soil fractions and organic C and N contents in the different soil fractions for each tree cover and soil depth. (**a**) and (**b**): Means and interactions for dry weight of soil fractions, (**c**) and (**d**): Means and interactions for organic C content, (e): Means and interaction for N content. Measurements were taken in Ranchillo Alto, November 2015

(Fig. 3.6c, e). Organic C content was higher at the 0–5 cm soil depth for both forests types (Fig. 3.6d).

The C contents in the different fractions are similar to those reported by Huygens et al. (2005) for a secondary *N. obliqua* forest in southern Chile and to those reported by Dube et al. (2009), Dube and Stolpe (2016), and Alfaro et al. (2018). The LF presented the higher C and N contents (Fig. 3.6c, e) because the LF is formed by undecomposed OM of plant origin (Haynes 2005).

3.5 Conclusions

The quality of the soil was better in the deciduous forest of *N. obliqua* compared to the mixed forest with *N. dombeyi* as dominant species. The quality of the residues that are entering in the soil can stimulate the activity of the biota and especially the soil microorganisms, which would lead to higher values of the different indicators evaluated.

The no difference in the amount of light fraction and macroaggregates (labile OM) between the forest types, and the higher carbon and nitrogen contents in the light fraction presented in the *N. obliqua* forest, lead us to the conclusion that the quality of the organic matter of the residues that enter to the systems possibly varies much more than the amount of residues.

The light fraction was the most important measured sink for nitrogen and carbon in the soil aggregates. The amount and composition of this LF organic matter could play an important role in carbon and nitrogen cycling and retention in the soil.

The silvopastoral system that is currently being established will definitely help restore the most degraded sites through improvement of the soil quality. The knowledge acquired will permit state agencies to assess the global sustainability of these innovative practices in order to develop new standards on the adequate and efficient use of natural resources.

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4 Assessment of Trees Outside Forests (TOF) with Emphasis on Agroforestry Systems

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Abstract

Trees outside forests (TOF) have recently assumed importance in view of their economic, ecological, and climatic role. As a result, several countries have extended their scope to include TOF in their national forest inventories (NFIs) and landscape inventory systems. However, a huge variability exists in its assessment approach across different countries. Moreover, TOF definition, classification, assessment techniques, and monitoring methodology are suffering lack of attention in terms of uniformity across the globe. The present work focusses on TOF resources, nomenclature, and suitability of assessment methods for monitoring TOF cover and biomass inventory. TOF occur on different land use categories, making their assessment a little complicated. This chapter presents an overview of diverse and integrated techniques of assessing TOF using field methods complimented by robust remote sensing techniques. Field inventory methods are irreplaceable owing to their importance in establishing relationships with such advanced tools. Remote sensing applications have shown promising results in deciphering TOF resources recently by adopting multiple satellite data and classification techniques. A lot of case studies conducted in the past have demonstrated that optical, RADAR, and LiDAR (light detection and ranging) remote sensing methods do offer advantages over the traditional methods in terms of accuracy, time, and cost-effectiveness. Assessment of TOF is widely being recognized as an essential topic in sustainable natural resource management due to their role in offering variety of goods such as timber, fruits, and fodder as well

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as services like water, carbon, biodiversity, etc. TOF offer great potential for sequestering carbon and are high in case of agroforestry systems as compared to that of the dense canopy cover. Under the recent trend of urbanization, TOF are going to be important in climate amelioration in habitations. Another aspect is the existence of huge chunk of wastelands, which could be potential sites for hill agroforestry systems under TOF in view of enhancing carbon sinks under CDM and REDD+ mechanism. Carbon inventory assessment programs at national and international levels desire for adoption of latest methods including remote sensing and geographic information system (GIS) integrated with field inventory and advanced algorithms for qualitative and quantitative assessment of TOF resources.

Keywords

Trees outside forests (TOF) · Remote sensing · GIS · Agroforestry · Inventory assessment

4.1 Introduction

There is a strong recognition of trees outside forestsby policy makers, planners, and managers having a pivotal role in sustainable development. As defined by the FAO, trees outside forests have been identified to contribute to environment and socioeconomic well-being of mankind (FAO 2013). Trees outside forests (TOF) are attracting attention in view of pressure mounting on the existing forests due to increasing population and resource consumption (Plieninger et al. 2015). Unlike forests, TOF are present on all non-forest lands in varying densities and configurations, which makes them a resource rather than an area category (Beckschäfer et al. 2017). Agroforestry, one of the categorizations under trees outside forests, has immense potential in meeting day-to-day needs and food security of rural population. Trees outside forests are predicted to have a huge role in combating climate change. Some of the countries together with India have included trees outside forests under their national forest inventory programs after FAO's program for National Forest Monitoring and Assessment (NFMA) included TOF by default (Schnell et al. 2015b). However, a consensus needs to be built on bringing homogeneity to its definition across the globe in view of its ecological, climatic, cultural, and socio-ecological importance. A lot of policy makers and planners are critical of its inclusion in the forest resource inventory because of its ownership, dependence of rural livelihood, use, and short-term storage. There have been significant land use land cover changes in the recent past due to rapid urbanization and other developmental activities. A little has been done in terms of framing laws to check this rampant change of land use land cover. Additionally, there is an increasing challenge to assess these changes due to lack of database on trees outside forests inventory in most of the developing countries. Efforts are required to assess different categories of TOF resource and contribution in socioeconomic and cultural context of rural people, especially less empowered womenfolk. There is an essential requirement of advancement in technology for timely, accurate, and cost-effective assessment of agroforestry resources using remote sensing (RS) and geographic information system (GIS). A strong human resource development is needed at state and national levels to produce reliable estimates to supplement the global estimates of such resources in national communications reported for all countries by international bodies like United Nations Framework Convention on Climate Change (UNFCCC), Intergovernmental Panel on Climate Change (IPCC), and Food and Agriculture Organization (FAO). Policies and programs have to be devised for effective inventory and assessment of resources for effective land use planning.

Remote sensing has emerged as an important tool for assessing the forest resources rapidly, and such techniques are best suited to provide data in several key areas related to forest landscape patterns (Jensen 2000). Several studies have been carried out regarding applications of remote sensing technology (Mohan et al. 1990; Navalgund 2006; Navalgund et al. 2007). GIS helps in database creation, spatial data analysis, and integration and output generation (Maguire et al. 1991; Goodchild et al. 1992; Burrough and McDonnel 1998). It offers an important means of detecting and analyzing temporal changes, and since the early 1970s, satellite data have been commonly used for short-term (decade or less) change detection studies. These systems collect vast amounts of biological and physical data on multiple dates, thus allowing both inventory and monitoring of environment. RS and GIS are now providing new tools for advanced ecosystem management in the form of environmental modules in GIS software (Moore et al. 1993).

There is increasing focus placed on TOF by different countries in view of its inclusion in forest cover by many countries including India. Inventory assessment organization put emphasis on its presence, distribution, and density especially in areas where natural forests are scanty (FAO 2005).

4.2 Trees Outside Forests Terminology

TOF include trees extending from single isolated tree to systematically managed trees in varied agroforestry systems. The Food and Agriculture Organization (FAO) of the United Nations formulated the definition of TOF in the Global Forest Resources Assessment (FRA) 2000 and 2005 (FAO 2001, 2006). In simple terminology and according to the FAO, Trees Outside Forests are defined as "the trees on land not defined as Forest and Other Wooded Land (OWL)". 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). Trees are said to be TOF if they reach a height of at least 5 meters with area comprising of more than 0.5 hectares and should possess at least 5% canopy cover for trees or 10% for trees, shrubs, and palms combined. Trees that are used as shelterbelts, windbreaks, and riparian tree formation and are not found in agricultural or urban areas that have at least 25 meters length and less than 20 meters width are also considered as TOF (FAO 2002). Shrubs and palms are also included in TOF and may also be in the form of agroforestry trees, shade trees, fruit trees, as well as fodder trees.

Apart from coining the term TOF, the relevance of TOF for biodiversity, general environmental conditions, and human livelihood was also emphasized (Pain-Orcet and Bellefontaine 2004). TOF can be defined differently, and there seems to be country to country variation as far as its definition is concerned. Also, the basic definition given by the FAO depends on the definitions of forest and other wooded land. Therefore, many TOF definitions are available which often vary between countries (Lund 2002). The FAO has a keen interest in gathering information on TOF and encourages countries to carry out timely and high-quality assessments of TOF at national level (FAO 2010) and emphasizes the need for a better integration of TOF into the forest resource assessment reporting process (De-Foresta et al. 2013).

TOF have foremost role in the sustainability of agricultural production systems and hence aid secondarily toward the food security (IPCC 2000; FAO 2002; Schoeneberger et al. 2012). Several efforts are being made to plan a TOF classification system. The development of a gradient of characteristics that portray the resource (trees) including physical as well as functional attributes is a foremost contemporary issue. The gradient of characteristics also includes the land where the tree resource is present (Kleinn 2000; Gschwantner et al. 2009). On the basis of land use, TOF can be categorized as TOF restricted to built-up areas or TOF confined to agricultural lands. Tree resources found in built-up areas include trees confined to urban parks and gardens, trees restricted to streets, trees found as hedgerows, and trees along rivers and lakes and also include production systems encompassing orchards. TOF confined to agricultural lands include tree resources which grow in grasslands and meadows (windbreaks, scattered trees, woodlots, and other silvopastoral systems), in amalgamation with annual crops on agricultural fields (cocoa, coffee, and other systems), and trees grown in orchards or along water bodies and permanent crop systems (Bellefontaine et al. 2002). Spaced out from agricultural and urban lands, TOF can also grow on natural areas as a part of savannas and in mountainous areas at a tree line. TOF tree density is therefore typically very low. However, the scheme of classification of TOF followed in India is to stratify TOF resources into three strata, namely, block, linear, and scattered (FSI 2015).

4.3 Trees Outside Forests Inventory Assessments

4.3.1 Field Inventory Methods

Planted forests under the purview of trees outside forests form large-scale tree plantings to achieve the production of timber, fodder, and fiber, protection of catchments, and preservation of habitats. However, such tree plantings at smaller scale are attributed to agroforestry systems or community woodlots offering goods and services to the rural population. Examples of these systems in tropical countries include home gardens, alley cropping, improved fallows, intercropped trees, hedgerows, and fence lines. Such systems in temperate regions include tree, pasture

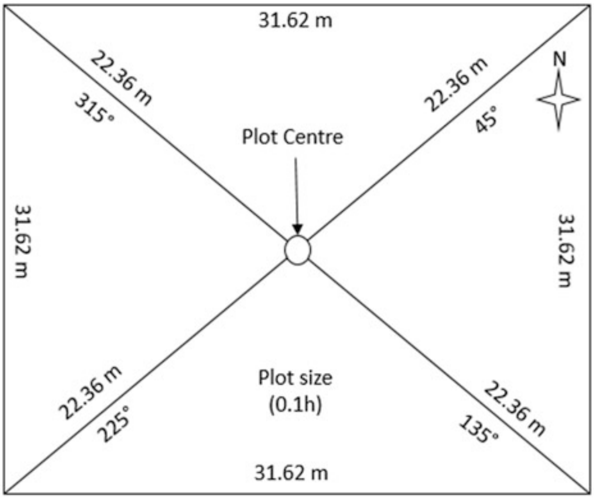

Fig. 4.1 Plot layout in the block stratum of TOF rural adopted by FSI

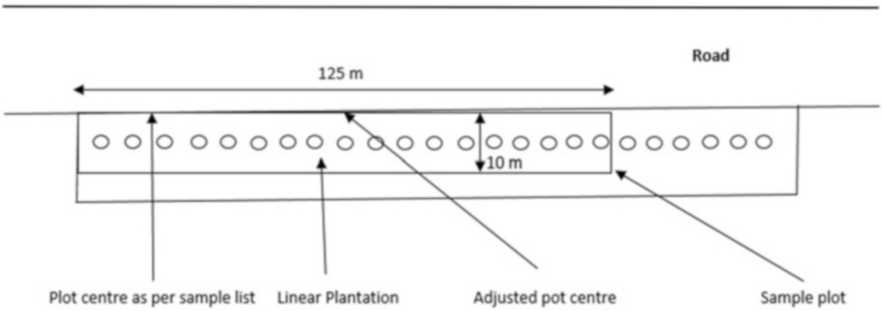

Fig. 4.2 Plot layout in the linear stratum of TOF rural adopted by FSI

and livestock combination, fruits with vegetable or grain crop, windbreaks, and shelter belts. In the urban and peri-urban landscapes, such systems may be represented by trees along roads and waterways and tree lots at parks and public places maintained for aesthetic, environmental, and recreational value (Long and Nair 1999).

Forest survey of India uses two-stage stratified sampling design for inventory of TOF at national level. In the first stage, sample plots spread over the 14 physiographic zones with district as the first stage sampling unit being selected for detailed inventory of TOF (rural and urban) on a cycle of 2 years. In the second stage, separate methodology is used for rural and urban inventory. In TOF rural assessment, district is further stratified into block, linear, and scattered strata. Square plots of 0.1 ha, rectangular plot of 10 m × 125 m, and square plots of 3.0 ha form the sampling units of block, linear, and scattered strata with a sample size of 50, 60, and 60, respectively (Figs. 4.1 and 4.2). However, in hilly districts, 95 square plots of 0.5 ha size will be located and surveyed (Pandey 2008; FSI 2019).

Sampling frame for urban areas prepared by the National Sample Survey Organization (NSSO) divides the whole urban centers of a district in Urban Frame Survey (UFS) blocks. FSI for TOF in urban areas adopts these UFS block as sampling units. Using stratified random sampling, FSI picks up 10%, 5%, and 2.5% of UFS blocks from districts with less than 500, between 500 and 1000, and more than 1000 blocks, respectively, distributed proportionately in five classes of towns based on census classification.

The areas of selected UFS blocks are computed with the help of Global Positioning System (GPS) during the field inventory. For estimating tree cover, the crown diameter of each tree falling in the selected UFS block is recorded. With the help of crown diameter, the tree cover of each UFS block is computed following the same approach as in case of scattered stratum. The total tree cover for a selected district is obtained by aggregating the area of tree cover under block, linear, and estimated area of scattered and urban strata. On the basis of tree cover of sampled districts, the tree cover in each physiographic zone is estimated. Adding estimates of tree cover of all the physiographic zones, tree cover at country level is obtained.

Singh and Chand (2012) adopted a sampling design according to FSI field manual in order to assess TOF aboveground biomass using field data and remote sensing technique. The dimensions of the sampling plot were taken variably with block strata (32 m × 32 m), dense scattered tree (50 m × 50 m), sparsely scattered tree (100 m × 100 m), and 50 × total width with plantation for linear strata, viz., road, canal, and railway line. For estimation of tree cover in rural area of selected districts, the area under block and linear stratum is directly obtained from classified map of TOF districts. The area under scattered stratum is estimated on the basis of crown diameter of trees recorded during the field inventory. Using crown diameter, tree cover of each sample plot is computed, which is then converted into equivalent notional area corresponding to 70% canopy density. Using tree cover area of selected plots and corresponding cultivable non-forest (CNF) area of district, estimate at district level is generated under scattered stratum.

To estimate the tree cover at state level, adequate sample size is not available. In such circumstances, small area estimation technique is used to generate synthetic estimation with better precision. Synthetic estimation has its strength in borrowing information from larger groups for use in small area or domain. It assumes that the relation of the study character as well as for the auxiliary character between larger and small areas remains the same. Accordingly, the state level estimates of tree cover were generated using synthetic estimators derived from physiographic zone level estimate of tree cover.

4.4 Remote Sensing Techniques for Assessment of TOF

Forests provide a great amount of ecosystem services, and at global level, significant exertions are being made into the monitoring of these forest resources. Therefore, assessment of TOF is nowadays accepted as a critical matter in sustainable natural resource management (FAO 2010; Pujar et al. 2014).

Table 4.1 Trees outside forests (TOF) monitoring at global and regional levels

Type of inventory	Type of sampling/data used	Place of monitoring	Reference
TOF field inventory (Indian NFI)	Forest inventory design of two-phase sampling	India	Tewari et al. (2014)
NFI-type survey (under NFMA program of FAO)	Stratified systematic cluster sampling	Tanzania	Vesa et al. (2010), Tomppo et al. (2014)
TOF inventory on farms	Classical forest inventory design of two-phase sampling	Kenya	Holmgren et al. (1994)
TOF resource inventory	MODIS data	11 Midwest states of USA	Perry et al. (2009)
TOF resources on agricultural land	MODIS VCF data	Global level	Zomer et al. (2014)
TOF inventory	IRS high-resolution panchromatic 2.5 m data with 5.8 m multispectral LISS IV data	Eastern Ghats in Khammam district of Telangana state of India	Pujar et al. (2014)
Apple orchard inventory	Indian IRS satellite data	Western Himalayan region of India	Kumar et al. (2008)
TOF inventory	IRS-P6 LISS IV satellite data	Southern part of Haryana, India	Singh and Chand (2012)
TOF inventory	LISS IV satellite data	Ganderbal (Central Kashmir region)	Mehraj (2018), Wani et al. (2018)

Based on the increasing impact of TOF on human society, monitoring on large area basis of this tree resource was put on the political agenda in the establishment of that period (FAO 2001). The present monitoring of TOF carried out in the current era is however tremendously variable across different countries of the world, and the schemes that are routinely used to monitor TOF are often missing or incomplete. However, an exception to this is the inventories carried out by the National Forest Monitoring and Assessment (NFMA) program of the Food and Agriculture Organization (FAO) of the United Nations (UN).

The first inventory of NFMA program was conducted in Costa Rica in 2000. Under this program, all trees that were present in the study area, usually a country, were included regardless of land use (FAO 2012). Thereafter, numerous national forest inventories (NFIs) began to include tree resources comprising of non-forest trees (Tewari et al. 2014).˙ The main reason for the inclusion of this valuable resource may be ascertained toward land use, land use change, as well as the forestry sector of the Kyoto Protocol. Furthermore, some countries are known to monitor TOF in the landscape inventory systems as well (Barr and Gillespie 2000). Some of the work regarding the monitoring of TOF can be abridged in Table 4.1.

Perry et al. (2009) carried out an assessment of TOF resources based on low-resolution optical data by making use of vegetation continuous field (VCF) product of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite.

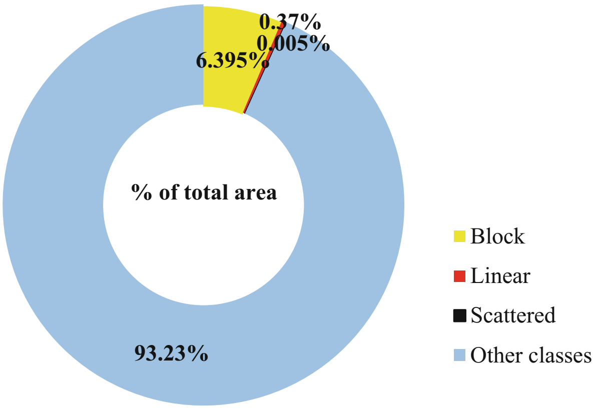

Fig. 4.3 Trees outside forests strata in Ganderbal district (2016). (Source: Wani et al. 2018)

By making use of MODIS data, another study was carried out by Zomer et al. (2014). They utilized MODIS data for assessment of TOF resources on agricultural land at a global scale. Through the usage of Global Land Cover 2000 database, tree cover from MODIS VCF data was co-analyzed. Their study revealed that more than 10% of tree cover is present in overall 43% of all agricultural land.

Making use of IRS satellite data, Kumar et al. (2008) carried out a study to map the apple orchards in the western Himalayan region of India. The satellite data was having a spatial resolution of 22.5 m and got an overall accuracy of 91.3%. However, their study area consisted mainly of barren topography where other woody vegetation did not exist. Another type of study was conducted on a forest edge region of dry deciduous forests of Eastern Ghats in Khammam district of Telangana state of India. This study was carried out by Pujar et al. (2014) utilizing IRS high-resolution panchromatic 2.5 m data (Cartosat-1 Orthorectified, acquired on March 16, 2008) used in tandem with 5.8 m multispectral LISS IV data (April 8, 2008). The linear TOF category showed the presence of 2.1 sq. km. Total TOF units (covering both clusters and single crowns) outlined were 54,012 of which dominating portion was by that of individual trees (40,567 trees). Patch TOF constituted 6330 units, whereas linear TOF category comprised of 7115 units. The study conducted by Schnell et al. (2015) revealed that in general remote sensing techniques revealing both horizontal and vertical structures of trees appear to be very promising for deriving auxiliary data regarding TOF.

Realizing the potential of technology in assessing TOF resources in Ganderbal district of Kashmir Himalayas, the study carried out by Mehraj (2018) using LISS IV data and on-screen digitization revealed that a significant 6.59% of land cover of the district falls under TOF. Using a double-staged classification, it was revealed that among all TOF strata, block stratum occupies maximum portion (6.395%), while linear stratum occupies 0.370% followed by scattered TOF with 0.005% (Fig. 4.3). TOF strata when further classified under different TOF practices revealed that horticulture covered maximum area (5.73%) of the total area, whereas scattered

Table 4.2 TOF practices of Ganderbal district (2016)

TOF strata	TOF practice	Area (ha)
Linear	Boundary plantation	421.35
Linear	Roadside plantation	46.69
Linear	Riverside plantation	75.95
Block	Horticulture	8384.17
Block	Woodlot	968.17
Scattered	Scattered patches with clumpy plantation	8.51
Non-TOF	Other classes	136,390.25
Total		146,295.10

Source: Wani et al. (2018)

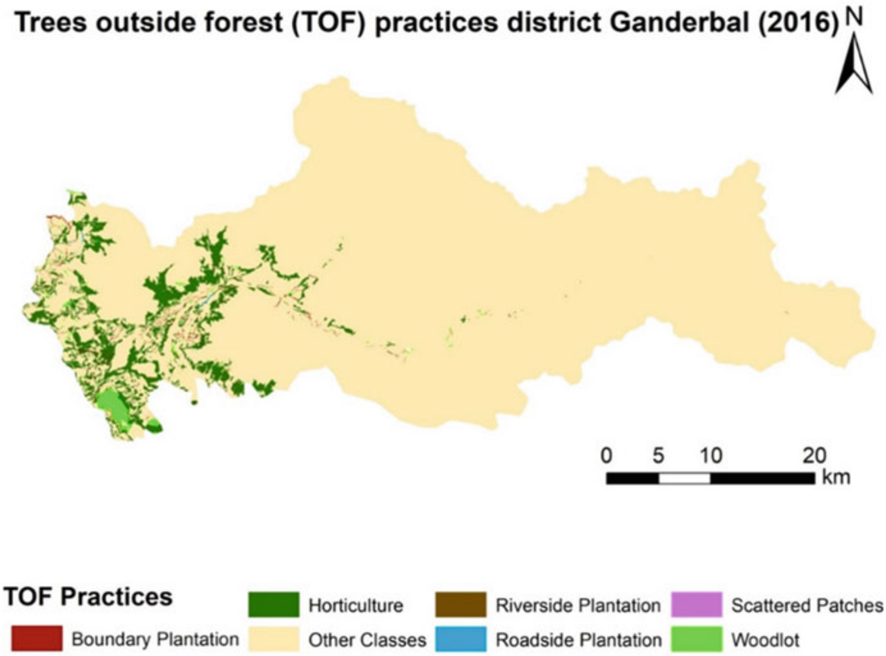

Fig. 4.4 Trees outside forests practices in Ganderbal district in Jammu and Kashmir, India, in 2016 (Source: Wani et al. 2018)

patches with clumpy plantation occupied minimum portion of the district (0.01%) (Table 4.2, Fig. 4.4).

Another study carried out by Wani (2019) used on-screen digitization of high-resolution LISS IV data and field inventory to assess TOF in the northern region of Kashmir Himalayas under JV Forest Division (Baramullah), Langate Forest Division (Kupwara), and Special Forest Division Tangmarg (Gulmarg area) (Fig. 4.5). The study assessed an average area of 9471.76 ha (3.62%) under TOF in the entire geographic region with the highest percentage of 5.47% (4928.91 ha) in Special

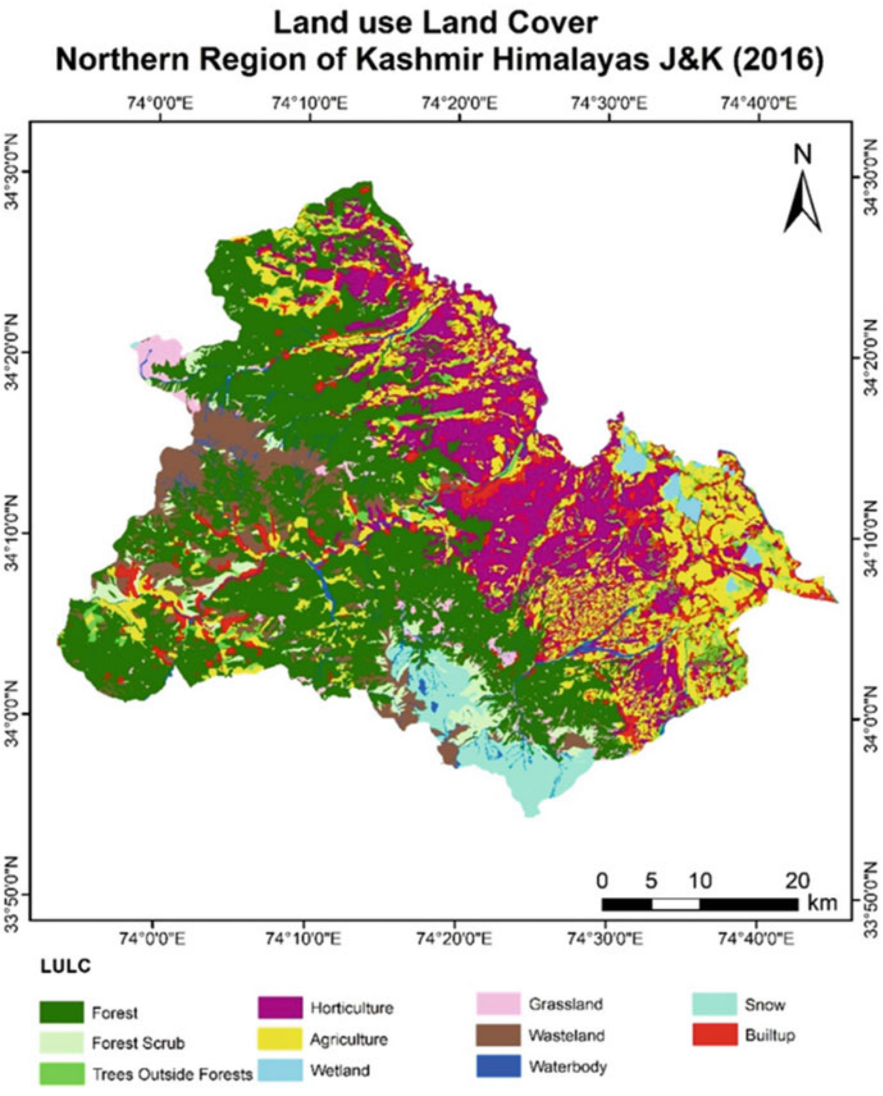

Fig. 4.5 LULC depicting TOF in northern region of Kashmir Himalayas in Jammu and Kashmir, India, in 2016 (Source: Wani 2019)

Forest Division Tangmarg. The same study estimates a large chunk of wastelands to the tune of 19441.13 ha (7.44%) in the region which could potentially be future TOF areas for enhancement of carbon stock to offset the impacts of climate change. Similarly, Wani et al. (2014) carried out TOF assessment in Kashmir region of northern Himalayas using Landsat data.

A large number of studies have been carried out on TOF resources worldwide in the last few decades for the purpose of TOF classification or estimation of biomass in

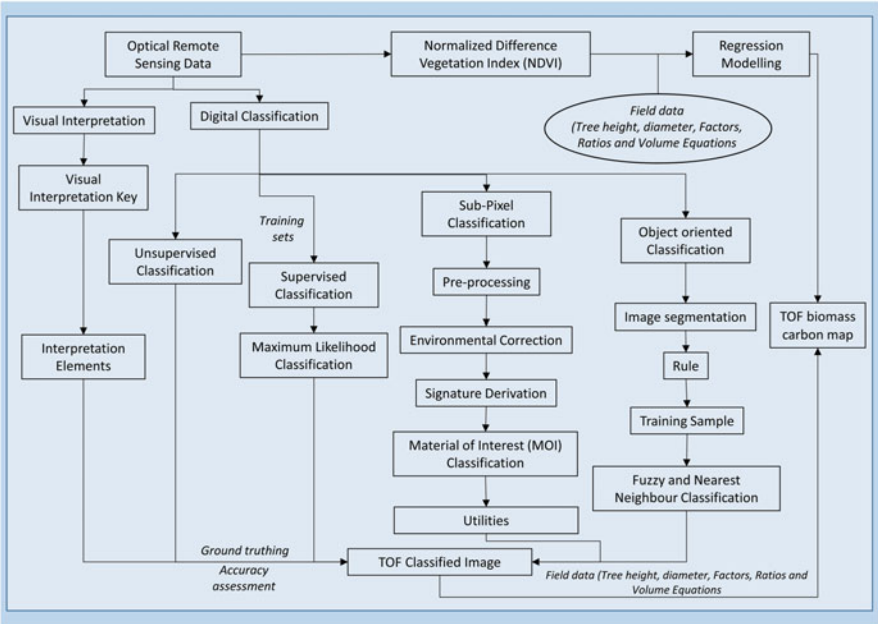

Fig. 4.6 TOF assessment using optical satellite data

TOF. Koukal and Schneider (2003) classified TOF on satellite imagery using automatic algorithms.

Since 1991, FSI has been assessing TOF through digital classification using LISS III and field inventory data. For rural inventory, high-resolution (LISS IV Mx) remote sensing data having a spatial resolution of 5.8 m was used for classification of TOF resources into block, linear, and scattered strata. Thereafter, optimum numbers of sample plots of specified sizes are laid out in each stratum for data collection. The optimum size and number of plots are determined through a pilot study. In case of urban inventory, optimum UFS blocks of NSSO are determined on the basis of survey results of pilot study. Application of optical remote sensing in TOF assessment is highly diverse depending on sensor resolution, scale of mapping, classification technique, etc. The decision to adopt a particular method depends on data availability and objective of mapping. A basic workflow of optical remote sensing-based TOF assessment is shown in Fig. 4.6.

Ashutosh and Roy (2010) used multispectral and panchromatic (PAN) data for mapping of TOF in Bijnor district of Uttar Pradesh. Patches of size greater than 0.014 ha (4 pixels of PAN data) were mapped with ground validation using the methodology. TOF for the district were estimated to be 2360.2 ha spread across five components based on size (0.025–1.0 ha, 0.1–1 ha, >1 ha) and distribution (TOF along road, TOF along canal).

Studies on such resources and the changes associated with them are essential at all levels of administration assuming their importance in sustaining forest-based industries, providing timber, fuelwood, and fodder besides preventing soil erosion and climate amelioration.

4.4.1 Sub-pixel Classification Technique

A sub-pixel classifier is a processing tool used in this study that is basically an add-on module to ERDAS IMAGINE geographic imaging package. In order to quantify the materials that are smaller than image resolution, sub-pixel classifier is highly envisioned. The concept stated by Schowengerdt (1995) forms the basis for IMAGINE sub-pixel processor, and the concept revealed that in a remotely sensed image data, the spectral reflectance of the majority of the pixels is assumed to be a spatial average of spectral signatures from two or more surface categories. Therefore, in an urban image, the brightness value of a pixel can be reflected as an amalgamation of spectral response from multiple materials, such as trees, shrubs, grass, cement roads, tarmac roads, metal roofs, wooden roofs, roadways, driveways, and car parks.

The sub-pixel processor is premeditated to classify each pixel in an image as its fraction of material of interest (MOI) present. A basic workflow of sub-pixel-based LiDAR (light detection and ranging)-based TOF assessment is shown in Fig. 4.6. For example, if the MOI is trees, each pixel in the image will hold a number from 0 to 1.0 representing the fraction of trees within the pixel. The sub-pixel analysis that can provide the relative abundance of surface materials within a pixel may be a prospective solution to per-pixel classifiers particularly while allocating with medium to coarse resolution satellite images (e.g., Landsat TM, MODIS, AVHRR). Numerous approaches are there for the sub-pixel analysis, viz., linear mixture models (Smith et al. 1990; Settle and Drake 1993; Van Dar Meer 1997; Wu and Murray 2003; Rashed et al. 2003), Bayesian probabilities (Wang 1990a, b; Foody et al. 1992; Eastman and Laney 2002; Hung and Ridd 2002), neural network (Foody and Aurora 1996; Zhang and Foody 2001), fuzzy c-means methods (Fisher and Pathirana 1990; Foody and Cox 1994; Foody 2000), and fuzzy set possibilities (Eastman 1999).

Myint (2006) generated urban vegetation maps using sub-pixel analysis, normalized difference vegetation index (NDVI), and expert system rules. Results from this study demonstrated the procedure to be fine that picked up signatures relatively well (Rizvi et al. 2016). In a study to assess carbon storage potential under agroforestry systems in Gujarat plains, sub-pixel classifier on LISS III data was used for estimating the extent of agroforestry areas. The extent was estimated to be highest in Dahod (12.48%) followed by Junagarh (10.95%). Spectral mixture modeling method using sub-pixel classification approach for classification of coconut was adopted using Landsat 7 ETM+ data (Palaniswami et al. 2006) with a sub-pixel accuracy of 87% based on digital number (DN) values and 93% based on radiance values.

Remote sensing analysis of agroforestry in Bathinda and Patiala districts of Punjab was carried out using sub-pixel method and medium-resolution (LISS III) data. Pixel-based classification revealed that the area under agroforestry was 7.09%

and 4.95%, respectively, in the two districts, while the area under agroforestry was found to be 14.76% and 13.25%, respectively, in case of sub-pixel-based classification (Rizvi et al. 2015). Sub-pixel classification of bald cypress and tupelo gum trees was carried out using Landsat Thematic Mapper Imagery. The study yielded improved results in comparison to traditional classification techniques (ISO-DATA clustering, maximum likelihood, and minimum distance) (Huguenin et al. 1997).

4.4.2 TOF Using Microwave Remote Sensing

The use of optical data is predominant in land use land cover mapping; however, its use is often limited by its availability and efficiency due to poor illumination and prevailing weather conditions particularly in the coastal regions and valleys. A radar system is comprised of an active sensor, illuminating a ground target area with its own energy signal, and the backscatter intensity of microwave radar data is independent of weather conditions. Interaction and scattering are the important features of radar surface which are dependent upon geometric and electrical conditions of the surface such as target material, orientation, moisture content, and surface roughness (Dobson et al. 1995).

Some of the important parameters of microwave remote sensing include wavelength, polarization, incidence angle, and spatial resolution. Imaging radars normally operate within a short range of wavelength with broad interval. The ascending order of wavelength in the active microwave region can be Ka, K, Ku, X, C, S, L, UHF, and P.

Each of these bands is having specific characteristics in relation to forest stand parameters. The X band gets scattered due to leaves and surface canopy and hence is useful in extracting information about the tree surface canopy. The C band can penetrate through leaves and gets scattered by small branches and under layer elements. The L band can penetrate through surface layers and hence gets scattered by the trunk and main branches. The P band having highest wavelength penetrates into the canopy, and majority of P band backscattering is observed due to trunk and trunk-ground reflectance. So, the backscatters of the P and L bands are the most related to the biophysical parameters of the trees.

The polarization characteristics of electromagnetic energy recorded by a remote sensing system represent an important variable used in different earth resource investigations (Campbell 2002).

The polarization refers to the direction of electric field in the electromagnetic waves while interacting between signals and the reflectors. Microwave sensors can emit the signals in horizontal (H) or vertical (V) polarizations. The synthetic aperture radar (SAR) data may have four polarizations:

1. HH: the emitted and backscattered signals have horizontal polarization.
2. HV: the emitted signal has horizontal and the backscattered signal has vertical polarization.

3. VH: the emitted signal has vertical and the backscattered signal has horizontal polarization.
4. VV: both emitted and reflected signals have vertical polarization.

Microwaveremote sensing has demonstrated potential in land use land cover classification including TOF due to its geometrical conformity to forests. A lot of studies using all weather-capable radar datasets have shown scope for forest classification using different techniques. A basic workflow of RADAR-based TOF assessment is shown in Fig. 4.7a. A similar analogy can be applied to study TOF with improvised methods and classification techniques. Nizalpur et al. (2011) demonstrated the potential of synthetic aperture radar (SAR) data in HH polarization in land cover classification over forested areas of Bilaspur, Chhattisgarh, using backscatter and interferometric coherence images with an overall classification accuracy of 82.5%.

Combination of microwave and optical remote sensing data is one of the hybrid technologies to improve the accuracy of land use land cover classification. There are several ways of combining these data types through fusion by pixel, feature, and decision-based approach. Several methods have been developed to integrate spectral and spatial information with Intensity Hue Saturation (HIS) being the frequently used (Welch and Ehlers 1987). However, principal component analysis is often used for data fusion to preserve the spectral integrity of the input dataset.

The C, L, and P bands are used in the biomass estimation in forests. The past studies have shown the longer wavelengths (L and P bands) and the HV polarization have the most sensitivity to the aboveground biomass (AGB) (Luckman et al. 1997; Kurvonen et al. 1999; Sun 2002). Applying the same analogy to TOF with modified processes and algorithms, radar data can potentially be applied to biomass estimation in TOF in regions where it is abundant. Nizalpur et al. (2011) in another study estimated aboveground biomass in Indian tropical forested area using multifrequency airborne DLR-ESAR data in C, L, and P bands over parts of Gujarat in India. Increase in backscattering coefficient was reported with the increase in biomass up to 70 Mg/ha in C band, 150 Mg/ha in L band, and up to 200 Mg/ha in P band.

S band has also been used for biomass retrieval in forests and TOF. Relationship of S band (7.5–15 cm) backscatter and MIMICS-I simulated radar backscatter to the different forest types (broadleaved and needle leaved) was studied to retrieve the biomass. The study observed increasing sensitivity to forest biomass with a saturation level of 100 t/ha in broadleaved forests for different polarizations (Ningthoujam et al. 2017).

4.4.3 TOF Using LiDAR Imaging

LiDAR (light detection and ranging) is a remote sensing method used to map the structure of vegetation including height, density, and other characteristics. A basic workflow of LiDAR-based TOF assessment is shown in Fig. 4.7b. A LiDAR system measures the time taken by emitted light to travel to the ground and back, and that time is used to calculate distance traveled. Subsequently, the distance traveled is converted to elevation. LiDAR makes it possible to measure vertical forest structure

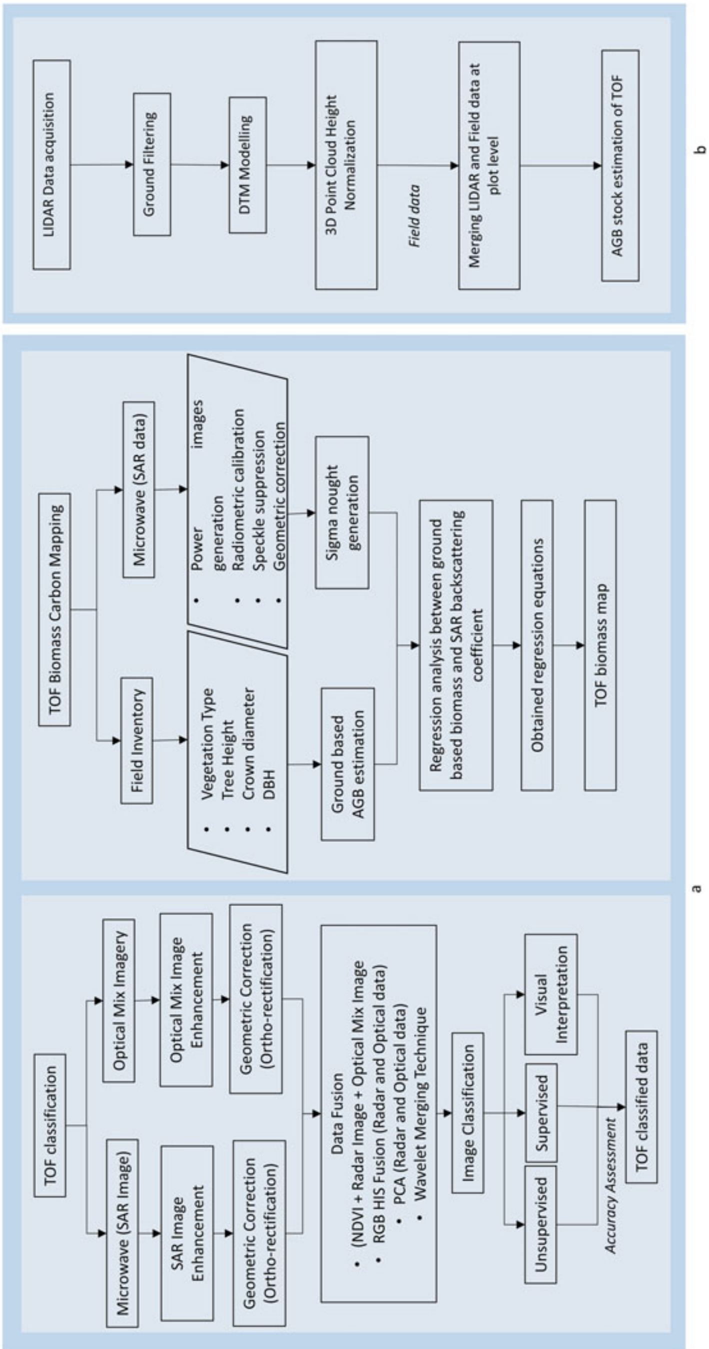

Fig. 4.7 TOF assessment using non-optical satellite data: (**a**) Microwave and (**b**) LIDAR

directly for estimation of height and biomass accurately up to 1300 Mg ha^{-1} (Means et al. 1999; Mitchard et al. 2012).

The study conducted by Lefsky and McHale (2008) conveyed that LiDAR data from terrestrial laser scanning appears to have a great potential to facilitate the development of biomass models and volume for TOF. They also concluded that with this technique, the entire 3D structure of trees can be revealed, and hence, terrestrial laser scanner data alone possess a great potential to make accurate tree volume estimates. Also, Eysn et al. (2012) proposed that LASER measurements are of special concern in TOF assessment because it is possible to describe both vertical and horizontal distribution of the vegetation. Such data can also be used for allocating part of schemes to estimate parameters such as total TOF biomass and can help in delineating the areas of interest. Mangla et al. (2016) conducted a study to estimate aboveground forest biomass of sal (*Shorea robusta*) in Timili Forest Range, Uttarakhand, India, using SAR and LiDAR data and adopting Random Forest Regression Model. Modeled output for aboveground biomass had a reliable accuracy (RMSE 27.68 Mg ha^{-1} and R^2 of 0.63).

LiDAR remote sensing has also assumed importance in forest inventory programs including TOF of some developed nations having high accuracy and reliability in comparison to traditional methods where errors due to inaccurate representation are propagated to outputs of spatial and process models. Johnson et al. (2015) used LiDAR data to predict biomass of TOF in all "non-forest" Forest Inventory and Analysis (FIA) plots in Maryland, USA. The TOF biomass thus computed revealed close agreement with field measurements upon validation. There was a significant increase of 15.6% in total tree biomass resulting from inclusion of TOF.

There is an emphasis on integrating technologies with field-based methods for improving the assessment of TOF resources. Very few countries have adopted detailed and illustrative methodologies for assessing TOF resources under their forest inventory programs. Schnell et al. (2015) advocate for optimizing sampling strategies for monitoring TOF and suggest two-phase sampling strategy with laser scanning in the first phase followed by a field inventory in the second phase. The structural pattern and distributive behavior of trees outside forests are different from forest trees. There is a need to evolve separate processes and models for biomass estimation in TOF.

4.5 Conclusion

In various categories of agroforestry, rural and urban forestry, and other sectors, TOF are usually found in fragmented manner and hence were often left out in the forest statistics, natural resource assessments, as well as in policy and legislation. Forests provide a great amount of ecosystem services, and at global level, ample exertions are being made uninterruptedly into the monitoring of these forest resources. Tree assets growing outside the forests offer akin services as that of forests and were normally not taken into consideration by forest monitoring programs. Nowadays, assessment of TOF is being accepted as a critical matter in sustainable natural resource management. Furthermore, foremost task for an enhanced appraisal of trees and their services can be best achieved by improving our understanding of the position and dynamics of all tree resources including TOF. TOF should be periodically inventorized and assessed for temporal changes using advanced and updated technology as they assume importance in sustaining forest-based industries, providing timber, fuelwood, and fodder, besides preventing soil erosion and climate amelioration. TOF offer a great opportunity to sequester carbon under different agroforestry systems, making their accurate assessment imperative. TOF also provide a unique way of combating climate change in cities by trapping carbon under urban forestry in the form of urban woodlots, roadside plantations, and trees inside urban parks, making their assessment extremely important in view of harnessing benefit under different climate change programs. With the existing area under wastelands, there is a huge potential to increase TOF through plantation drives involving local communities, nongovernmental organizations (NGOs), and state forest department officials targeting enhancing carbon sinks under CDM and REDD+ mechanism. Forest resource assessment (FRA) programs across the globe realizing the potential have started incorporating TOF in their inventory mechanism owing to strategic increase in carbon inventory. There is a global thrust for adoption of advance remote sensing tools for accurate, cost-effective, and timely assessments of forest and TOF resources.

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Part II

Agroforestry Interventions for Restoration and Environmental Services

Agroforestry Interventions for Rehabilitating Salt-Affected and Waterlogged Marginal Landscapes

5

Jagdish Chander Dagar and Sharda Rani Gupta

Abstract

Salinity-afflicted landscapes occupy nearly a billion hectares globally, representing about 7% of land area in more than 100 countries of the world. Asia, the Pacific, and Australia have almost 50% of the world's salt-affected lands and about two-thirds of the world's sodic soils. Waterlogging and salinity are major impediments to the sustainability of irrigated lands and livelihood to the farmers, especially the smallholders in the affected canal irrigated as well as non-irrigated areas. Considering the interest for arid and semiarid regions to improve biosaline agriculture through domestication and sustainable use of halophytic plants for food, fodder, medicine, and reclamation purposes, many workers have contributed toward developing technologies of growing halophytes in saline habitats and with the use of saline water for irrigation. Salt-affected lands can be utilized for producing food, fodder, timber, and fuelwood by incorporating trees with crops and forage grasses. Agroforestry systems for salt-affected lands include agri-silvicultural and silvopastoral agroforestry; fruit tree-based agroforestry systems; and trees for biodrainage, energy plantations, and agroforestry for dryland. Soil improvement in agroforestry systems is linked to build up soil organic matter, biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, increase in soil microbial activity, and the enhanced activity of arbuscular mycorrhizal fungi. In the southern Murray-Darling Basin Region of South Australia, carbon sequestration in plant biomass has been found to be significant, and the values ranged from 6.3 to 10.6 CO_2-e Mg ha^{-1} $yr.^{-1}$.

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Soil carbon sequestration in different biosaline agroforestry systems in India is estimated to be 99.33 to 35.28 CO_2-e Mg ha^{-1}. This chapter gives an overview of the salt-induced land degradation, characteristics of salt-affected soils, agroforestry techniques and practices for rehabilitation of salty and waterlogged landscapes for livelihood security, the role of agroforestry in soil bio-amelioration, soil nutrient enrichment, and carbon sequestration.

Keywords

Land degradation · Salt-affected soils · Waterlogging · Agri-silvicultural and silvopastoral agroforestry · Biodrainage · Soil enrichment · Bio-amelioration · Carbon sequestration · Biosaline agroforestry

5.1 Introduction

Salinity-afflicted landscapes, which now occupy nearly a billion hectares globally (about 7% of land area; Wicke et al. 2011), have their origin either due to natural geological phenomenon or anthropogenic factors (secondary salinization). The excessive irrigation in agriculture has mainly contributed to the increasing problems of secondary salinization, alkalization, and waterlogging (Szabolcs 1994; Rengasamy 2006; Qadir et al. 2007; Dagar and Minhas 2016). At present, salt-affected soils are reported to occur in more than 100 countries of the world where many regions are also affected by irrigation-induced salinization (Szabolcs 1989; Rengasamy 2006). The salt-affected area is reported to increase at a rate of 10% per year because of high evaporation, low rainfall, inadequate irrigation, and other anthropogenic activity (Himabindu et al. 2016; Liu et al. 2017; Mose et al. 2018). Waterlogging and salinity are major impediments to the sustainability of irrigated lands and livelihood to the farmers, especially the smallholders in the affected canal irrigated as well as non-irrigated areas. The salinity and sodicity constraints adversely affect crop yields and the provision of environmental services, which affects the livelihood of people dependent on soil and water resources of marginal lands (Qadir et al. 2007). In a recent estimate, salt-induced land degradation in irrigated areas may cost US$27.3 billion because of lost crop production (Qadir et al. 2014).

In different regions of the world, scientists are engaged in developing technology for improving salt-affected lands so that environmental services like biomass production, soil fertility, clean air and water, carbon sequestration, biodiversity, etc., could be improved. Considering the interest for arid and semiarid regions to improve biosaline agriculture through domestication and sustainable use of halophytic plants for food, fodder, medicine, and reclamation purposes, many workers have contributed toward developing technologies of growing halophytes in saline habitats and with the use of saline water for irrigation (Dagar and Minhas 2016; Dagar et al. 2016d; Dagar 2014, 2018) and also studied diverse ecophysiological mechanisms of several promising plant species (Yeo 1983; Flowers 1985; Koyro et al. 2008; Daoud et al. 2013). Agroforestry, which is a land-use system in which trees or shrubs are grown in association with agricultural crops, pastures, or livestock, is one such approach which can improve marginal salt-affected lands and sustain livelihood security (Dagar 2014). Agroforestry also increases biodiversity on degraded salty lands by enhancing numerous ecological and production functions. In the Murray-Darling Basin, land-use changes have caused the salinization of rainfed (Charman and Murphy 2007) as well as irrigated land (Tanji and Kielen 2002). The effect of salinity on ecosystem services such as food production and water quality in Murray-Darling Basin of Australia has been discussed with special reference to ecosystem services and management response by Holland et al. (2015).

Salt-affected soils need to be rehabilitated to improve food security, to reduce arable land shortages, and to address the ability to meet the food demand of an ever-growing human population (Yan et al. 2015). To bring the salt-affected wastelands under sustainable productive system and use poor-quality waters carefully in agriculture, innovative technologies using stress-tolerant halophytes of high economic value need to be developed (Dagar et al. 2016c, d). The improvement of soil carbon in agroforestry systems on salt-affected soils offers substantial global greenhouse gas mitigation potential (Wicke et al. 2013; Gupta et al. 2016). Salt-affected marginal land may provide an alternative land resource for the cultivation of second-generation food (*Chenopodium quinoa*, *Distichlis spicata*; Dagar 2018) and biomass crops such as *Miscanthus* (Oliver et al. 2009) and *Jatropha curcas* on highly sodic soils (Singh et al. 2013). The salt-affected lands can be brought under viable vegetation cover by using suitable planting techniques and making use of salt-tolerant plant species. Soil rehabilitation by the use of suitable agroforestry systems is an effective way to both productively utilize and desalinize salt-affected lands in India, Central Asia, western Australia (Dagar 2014; Gupta and Dagar 2016; Vargas et al. 2018), and some African regions (Qureshi et al. 2018). Rumman et al. (2013) studied the use of saline water (ECe 13 dS m^{-1}) to grow turfgrass species such as *Paspalum vaginatum*, *Sporobolus virginicus*, *Distichlis spicata*, and *Pennisetum clandestinum* and found that in dry regions *S. virginicus* and *D. spicata* having high salinity tolerance showed greater potential as turfgrass.

This chapter gives an overview of the salt-induced land degradation, characteristics of salt-affected soils, agroforestry techniques and practices for rehabilitation of salty and waterlogged landscapes, soil enrichment and bio-amelioration, and carbon sequestration.

5.2 Salt-Induced Land Degradation

Soil salinization is one of the major causes of land degradation that impacts soil fertility and is a significant component of desertification processes in the world's dry land. The global area of salt-affected lands has been reported to occupy from 400 Mha to 960 Mha, depending on the datasets and the classification systems used (Szabolcs 1989; FAO 2001, 2008; Wicke et al. 2011). According to FAO (2015), the global extent of saline and sodic soils is 831.4 Mha (Table 5.1).

Table 5.1 Area of salt-affected and sodic soils in the world (million hectares)

Regions	Total area	Saline soils	Percent	Sodic soils	Percent
Africa	1899.1	38.7	2.0	33.5	1.8
Asia and 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	2038.6	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 (2015)

Based on this estimate, Asia, the Pacific, and Australia have almost 50% of the world's salt-affected lands and about two-thirds of the world's sodic soils. About one-third of Australian soils are sodic, some in the natural condition and others through land management (McFarlane et al. 2016).

Salt-affected soils occur worldwide with large areas in the Aral Sea Basin in Central Asia, the Yellow River Basin in China, the Euphrates Basin in Syria and Iraq, the Murray-Darling Basin in Australia, and the San Joaquin Valley in the United States (Qadir et al. 2014). In India, about 6.75 Mha of land is either sodic or saline (Mandal et al. 2010), and 6.41 Mha of land is degraded due to waterlogging. In Pakistan, nearly 6.3 million ha of land is affected by different levels and types of salinity, out of which nearly half is under irrigated agriculture, especially in Indus Basin (Qureshi et al. 2008). Salt-affected soils also represent a significant problem throughout China, and the total salt-affected soils cover about 36 Mha, which occupy 4.88% of usable land; about 9 Mha of arable land is salt-affected, accounting for 6.62% of the total land (Yang 2009; Liu et al. 2015). The main driving factors of evolution of salinization in China are inappropriate water resource and land management as well as climate change.

Based on the data extracted from the soil map of Iran (in digital format), slightly and moderately salt-affected soils cover about 25.5 million ha, while soils having high salinity levels occupy 8.5 million ha (FAO 2000). Qadir et al. (2008a, b) have synthesized the information on the sources of salts in Iranian soils along with the extent and characterization of salt-affected soils. Salinization is one of the major problems in arid and semiarid areas of Central Asia because of continuous use of the major rivers including Amu Darya, Zarafshan, and Syr Darya for irrigation to raise crops, which has resulted in rising water tables, waterlogging, and saline lands in the whole Aral Sea Basin (Toderich et al. 2013). Salt-affected lands in Central Asian region are the most characteristic features of natural continental terrestrial salinization, sodication, and alkalinization (Toderich et al. 2013). These soils are characterized by low organic matter ($< 1.0\%$), high salt contents, and poor water-holding capacity (Toderich et al. 2013).

About 1.82 million hectares of irrigated cropland in California is affected to some degree by soil salinization; most of the seriously affected acreage is in the Imperial

Valley in Southern California and the Western San Joaquin Valley in Central California (Letey et al. 2002). In the San Joaquin Valley in the United States, salt buildup in soils and groundwater is threatening the productivity and sustainability of otherwise highly productive lands (Schoups et al. 2005).

In Australia, land clearing for agriculture removed the original native vegetation, which resulted in dryland salinity, because of a rising saline water table, affecting over 90% of the agricultural lands (Stirzaker et al. 2002). It has been estimated that at least 180,000 ha of north-southwest of Australia is currently affected by dryland salinity or has shallow water tables less than <2 m deep (Johnson et al. 2009). Dryland salinity is characterized by the presence of salts in the soil or groundwater because of anthropogenic land use change (see Holland et al. 2015). Irrigation-induced salinity occurs because excess water applied to crops travels beyond the root zone to groundwater resulting in the rise of the water table and salt buildup in the surface layer of soil.

Soil salinization is one of the major constraints in achieving food security and reducing environmental and biodiversity degradation in Ethiopia (Qureshi et al. 2018), and salinity causes low farm and livestock productivity. It is estimated that salt-affected lands (saline and sodic) cover a total area of 11 million ha, being the highest in any African country (Fantaw 2007). Most of these soils are concentrated in the plain lands of arid, semiarid, and desert regions of the Rift valley system including Afar, the Somali lowlands, the Denakil plain, and valley bottoms throughout the country (Fantaw 2007).

Natural or primary salinization and sodification are quite common in the arid and semiarid regions of Latin American countries, including in Mexico, Cuba, northern South America, Peru, northeast Brazil, and southern Argentina (FAO and ITPS 2015). It has been estimated that 18.4 million ha in Latin American countries is affected by salinization caused by irrigation, land clearing, and overgrazing (see FAO and ITPS 2015).

5.3 Characteristics of Salt-Affected Soils

Primary salinity refers to the buildup of salts as a result of natural causes such as lithological inheritance or increased evapotranspiration in arid zones. Primary salinity occurs naturally in soils and waters. Natural salt accumulation processes are associated with certain types of relief, geomorphological, and hydrogeological conditions. Secondary salinity involves anthropogenic activities related to inappropriate irrigation management using both freshwater and saline water without drainage provision, groundwater depletion, and/or seawater intrusion. Soil salinization affects approximately 33% of the world's irrigated land and can cause damage to biodiversity, agriculture, and water sources (FAO SPUSH 2000).

Attempts were made to classify the soils on the basis of total soluble salts measured in terms of electrical conductivity of the soil's saturated paste extract (ECe) or various dilutions (soil: water 1:2 or 1:5), exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR), and pH of the saturation paste (pHs) or

Fig. 5.1 Typical sodic soil at Bichhian in northwest India (left); soil profile of typical sodic soil (right)

other dilutions. The US Salinity Laboratory Staff in 1954 (USSL 1954) originally proposed the three categories of salt-affected soils on the basis of these parameters, i.e., saline, saline-alkali, and alkali soils. The definitions in respect of these three categories were slightly modified later by the Soil Science Society of America (SSSA 1987). It was described that owing to excess salts (ECe 4 dS m^{-1}) and absence of significant amount of sodium (ESP <15, pH < 8.2), saline soils are generally flocculated. The electrolytes causing salinity are generally chlorides and sulfates of sodium. Saline soils have high osmotic pressure of soil solutions which induces physiological drought and tissue injury due to direct toxic effects of individual ions and complex interactions between sodium, calcium, and magnesium. These soils are predominant in arid and semiarid regions.

The alkali soils are characterized by the presence of carbonates and bicarbonates of sodium and the sodium ions capable of alkaline hydrolysis causing high pH (>8.5) and ESP (>15), and electrical conductivity is low (ECe < 4 dS m^{-1}). A saline-alkali soil (ECe 4 dS m^{-1} or more; ESP 15 or more) was described similar to that of saline soils as long as sufficient salts are present, whereas upon leaching, these soils become alkaline (pH 8.5) leading to dispersion, and their permeability reduces to levels that can affect crop growth. The term "alkali" was discarded later on to be replaced with "sodic," and these soils contain sufficient exchangeable sodium (ESP 15) to affect the physical behavior of soils and interfere with the growth of most of the crops. The sodic soils are low in soil organic matter. Sodic soils at Bichhian in northwestern India are highly sodic having pH more than 10.2 up to a depth of 2 m (Fig. 5.1). The most peculiar feature of the soil profile was the presence of precipitated $CaCO_3$ layer at various depths of soil resulting in low soil permeability and impeded drainage; the $CaCO_3$ content varied from negligible in the surface layer of soil to as high as 20% at about 1-meter soil depth (Kaur et al. 2002a; Singh and Dagar 2005). The precipitation of calcium in alkali soils causes deposition of thick $CaCO_3$ layer known as *kankar* pan.

Soil sodicity results in the dispersion of soil particles, which in turn causes a poor soil structure with low aggregate stability (Sumner 1993; Qadir and Schubert 2002). The poor soil structure caused by high sodicity has adverse effects on the soil water balance and plant development (Qadir and Schubert 2002). Due to low plant development, organic residue inputs into the soil are reduced, leading to low soil organic matter (OM) contents (Wong et al. 2010).

The saline-sodic soils are characterized by high levels of soluble salts as well as sodium ions, ECe > 4 and SAR>13, that cause harmful impacts on all types of crop plants. Saline-sodic soils are characterized as the soils that have ECe > 4 dS m-1, pH > 8.5, SAR > 13 (mmol $L^{-1})^{1/2}$, and ESP > 15. Szabolcs (1989) also recognized magnesium, gypsiferous, and acid-sulfate soils as important salt-affected soils. Soils affected by magnesium when plowed form large clods that impede water flow resulting in poor water distribution and plant growth (Vyshpolsky et al. 2008),

Soils are considered waterlogged when the water table fluctuates within the crop or plant root zone. Typically, when the water table reaches within 1.5–2.0 m of the ground surface, the soils are considered waterlogged or potentially waterlogged. Waterlogged soils can be saline, saline-sodic, and sodic soils. In the case of dryland salinity, rising groundwater mobilizes salt stored in the soil profile into the root zone of plants and trees and concentrating at the soil surface through evaporation (see Stirzaker et al. 2002). About one-third of the world's irrigated area faces the threat of waterlogging. About 60 Mha of agricultural land is already waterlogged and 20 Mha salt affected (Heuperman et al. 2002). Waterlogging causes more harmful effects on crop production in the presence of shallow saline groundwater table because salts are built up in the soil surface through the capillary action (Houk et al. 2006). It also produces deleterious effects on water and nutrient uptake by crop.

5.4 Agroforestry Systems for Rehabilitation of Salt-Affected Lands

Conventional agriculture is usually not considered economically viable on salt-affected soils due to low crop yields and low economic returns (Qadir and Oster 2004), while physical remediation of salt-affected soils is complex, expensive, and time-consuming for farmers due to lack of proper guidance and training. Therefore, for these soils, forestry and agroforestry systems have been found to be an attractive alternative (Wicke et al. 2013; Gupta and Dagar 2016). Salt-tolerant tree plantations can be established on salt-affected degraded lands for phytoremediation purposes to reverse salt-induced land degradation and provide a source of energy and other products for rural households. The various agroforestry interventions for reclaiming salt-affected soils are comprised of agri-silvicultural, silvopastoral, and fruit-based agroforestry systems and trees for biodrainage, energy plantations, halophytic plants to remediate soil, and agroforestry for dryland salinity (Wicke et al. 2013; Gupta and Dagar 2016, a, b; Dagar and Minhas 2016) as depicted in Table 5.2.

Table 5.2 Some prominent agroforestry systems on salt-affected lands in India, Central Asia, and western Australia (GW = groundwater)

Saline environments and study locations	Agroforestry system, role of trees	Reference
Moderately alkali soil CSSRI, Karnal	Agri-silviculture—*Populus deltoides*, *Eucalyptus tereticornis*, and *Acacia nilotica* with crops (income generation, soil improvement)	Singh et al. (1997)
Reclaimed sodic soil CSSRI, Karnal	Tree plantation of *Grevillea robusta* (carbon sequestration, income)	Jangra et al. (2010)
Moderately alkali soil at Salimpur, Kurukshetra	Age-old Agri-silvicultural system of *Eucalyptus tereticornis* with sugarcane and wheat crop (carbon sequestration, income)	Gaur (2013)
Degraded saline lands, Central Asia	Agri-silvicultural – *Tamarix*; *Elaeagnus angustifolia* with legume crop; fuelwood production and restoration	Toderich et al. (2013)
Sodic soil, presence of precipitated $CaCO_3$ layer at various soil depths, Bichhian, Haryana, India	Silvopastoral agroforestry systems, tree species of *Acacia nilotica*, *Dalbergia sissoo*, and *Prosopis juliflora* along with salt-adapted grasses; timber, fuelwood, carbon sequestration, soil amelioration	Kaur et al. (2002a, b); Singh and Dagar (2005)
Clay loam saline vertisol, Gujarat, India	Silvopastoral systems with *Salvadora persica* and grass species of *Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*	Rao et al. (2003)
Saline water irrigated semiarid soils, Hisar, Haryana, India	Silvopastoral system of *Acacia nilotica*, *Salvadora persica* with native grasses	Kumari et al. (2018)
Saline water irrigated semiarid, hyperthermic camborthids soils, Hisar, Haryana, India	Fruit-based agroforestry systems (income generation)	Dagar et al. (2016d)
Moderate alkali soils,CSSRI, Karnal, India	Agroforestry based on medicinal and aromatic crops (income)	Dagar et al. (2009a, b)
Saline-sodic topsoil, sodic subsoils, waterlogged, Puthi, Haryana, India	Agroforestry for waterlogged areas (reclamation, income, carbon sequestration)	Jeet-Ram et al. (2007); Dagar et al. (2016a)
High soil sodicity with calcareous hard pans + fresh groundwater; Lucknow, India	Energy plantation with *Jatropha curcas*, a biodiesel plant (energy, soil amelioration)	Singh et al. (2013)
Dryland salinity, water tables 1 to 3 meters belowground, salinity 5 to 30 dS m^{-1}, Narrogin, western Australia	Agroforestry for dryland salinity, saline alley farming (income, soil amelioration)	Stirzaker and Lefroy (1997)
Dryland salinity; southwest and western Australia	Agroforestry system with alley cropping of wheat; alley farming; short rotation farming (income, soil amelioration)	Archibald et al. (2006); Harper et al. (2012)

Adapted from Gupta and Dagar (2016); Dagar and Minhas (2016)

5.5 Evaluation and Productivity of Agroforestry Systems

During the past two decades, interesting work has been carried out related to afforestation of salt-affected landscapes. Technologies of tree plantation have been evolved, and many salt-tolerant species have been evaluated and identified, particularly in Indian subcontinent and Australia (Singh et al. 1988; Qureshi et al. 1993a, b; Singh et al. 1993, 1997; Tomar et al. 1998, 2003a, b; Dagar et al. 2001a, b; Barrett-Lennard 2003; Singh and Dagar 2005; Qadir et al. 2008a, b; Dagar 2014; Dagar and Minhas 2016; Dagar et al. 2005, 2006a, b, 2016c). The auger hole planting technique for establishment of tree saplings in sodic soils, developed by Central Soil Salinity Research Institute, has played a vital role in terms of success in sapling establishment, reducing cost of plantation, and practical adaptability. In this technique, the iron-made auger is mounted on a tractor and used for making holes of dimensions 20–25 cm diameter and 1.2–1.8 deep piercing the *kankar* (cemented $CaCO_3$ layer) (Fig. 5.2). These holes are re-filled with original soil mixed with limited quantity of amendments (3–5 kg gypsum and about 5 kg farmyard manure per auger hole) so as to manage the root zone by modifying the soil environment to greater soil depths, and tree saplings are planted in these pits and irrigated.

5.5.1 Agri-Silvicultural Systems

Many tree species have been evaluated and successful species identified for their suitability for sodic soils of different pH (see Dagar et al. 2001b; Singh and Dagar

Fig. 5.2 Afforestation of highly sodic soils (pH > 10), making auger holes to pierce *kankar* pan ($CaCO_3$ layer) for planting tree sapling (Source: CSSRI, Karnal)

2005; Dagar 2014). *Prosopis juliflora*, *Tamarix articulata*, and *Acacia nilotica* are most successful for high pH (>10) soils, while for moderate alkali soils (pH < 10), *Terminalia arjuna*, *Eucalyptus tereticornis*, *Casuarina equisetifolia* (frost sensitive), *Pongamia pinnata*, *Pithecellobium dulce*, *Cassia siamea*, *Parkinsonia aculeata*, and *Azadirachta indica* have been found suitable trees. The biomass of different tree species was measured by Dagar et al. (2001b) and Singh et al. (2008) when grown in high pH soils which ranged from 19 Mg ha^{-1} (*A. indica*) to 93 Mg ha^{-1} (*T. articulata*) depending upon the performance of a species. Despite of getting good biomass trees also helped in amelioration of soil. After 10 years of growth, the organic carbon in soil increased from initial 0.8 g kg^{-1} to 2.7 g kg^{-1} (in *C. siamea*, *P. dulce*, and *A. indica*) to 4.3 g kg^{-1} in *P. pinnata* and 4.5 g kg^{-1} in *P. juliflora*. Tomar et al. (1998) reported subsurface and furrow planting to be the suitable method for waterlogged saline soils and also for establishment of saplings using saline water. They also evaluated many tree species in waterlogged saline soils and found that after 9 years of plantation, *Prosopis juliflora* and *Casuarina glauca* produced the highest biomass (98 and 96 Mg ha^{-1}, respectively), followed by *Acacia nilotica* (67 Mg ha^{-1}) and *Acacia tortilis* (41 Mg ha^{-1}) when planted with subsurface or furrow technique. *Salvadora oleoides*, *S. persica*, *Parkinsonia aculeata*, *Acacia farnesiana*, and *Tamarix articulata* were other successful trees in saline waterlogged conditions and could be planted successfully in soils having salinity of ECe 30–40 dS m^{-1}, and species such as *Acacia nilotica*, *A. tortilis*, *A. pennatula*, *Casuarina glauca*, *C. obesa*, *C. equisetifolia*, *Callistemon lanceolate*, *Eucalyptus camaldulensis*, *Leucaena leucocephala*, and *Feronia limonia* could be grown on sites having soil ECe from 10 to 20 dS m^{-1}.

In Pakistan, Hafeez (1993) and Qureshi et al. (1993a, b) reported the results of many trials conducted with exotic and indigenous trees in saline alkali soils having pH 9.5, ECe 10–15 dS m^{-1}, and SAR 116 and found that *Eucalyptus camaldulensis* was the most successful species under a variety of salinity conditions while *Leucaena leucocephala* was observed as an aggressive species under moderate salinity and *Tamarix articulata* showed rapid growth under low salinity. *Eucalyptus* is a fast-growing tree with lesser canopy, making it more suitable as agroforestry tree, particularly in irrigated conditions. Many suitable clones have been developed in India from *E. tereticornis, E. camaldulensis*, and hybrid *Eucalyptus* (*E. botryoides* × *E. tereticornis* and *E. robusta* × *E. tereticornis*). Some progressive farmers planted three salt-tolerant clones (C-3, C-7, C-10) on bunds (1 m × 1 m space on acre line) along with food crops, mainly rice-wheat and harvested on an average 30 Mg ha^{-1} per year wood biomass (harvested after 6 years of growth).

In *Acacia*, *Eucalyptus*, and *Populus*-based agroforestry systems on moderately alkali soils at CSSRI, Karnal, there was improvement in biological production due to improvement of soil organic matter and availability of soil inorganic nitrogen (Singh et al. 1995, 1997). The crops of Egyptian clover (*Trifolium alexandrinum*), rice, wheat, and mustard could successfully be grown in this system during the initial three years. After that, these crops planted initially were replaced with shade-loving turmeric (*Curcuma longa*). Irrigation of these intercrops helped *Populus* and *Eucalyptus* grow faster but adversely affected the growth of low water demanding trees like *Acacia*. Among tree plantations, *Populus* was the most profitable followed by *Acacia* and *Eucalyptus*. Thus, the agri-silvicultural systems on moderate alkali soils were found to be economically viable in terms of food, fodder, timber, and firewood production system as well as practicable for soil carbon sequestration in the long term (Singh et al. 1997).

Prosopis cineraria is the favored tree for agroforestry in dry regions of India as it fixes large amounts of nitrogen and does not affect the growth of crops under the canopy but rather exerts a boosting effect on the yield of crops growing in its vicinity. The tree grows successfully in highly saline (ECe $>$ 15 dS m^{-1}) and alkaline soils (pH values up to 9.8). The biomass of pearl millet (*Pennisetum typhoides*) crop was three times higher when grown along *P. cineraria* soil as compared to that of an open soil. It is highly drought tolerant; its taproot can reach groundwater at 20 m depth. Soil nitrogen, phosphorus, and potassium were higher under its canopies than in open fields (Aggarwal et al. 1993).

Crop-based management options and the effects of different types of re-vegetation for reclaiming saline soils have been investigated in some studies in Iran (see Qadir et al. 2008a, b). *Tamarix* and *Atriplex* plantations have been found as effective species in decreasing the salinity of surface soil (Guiti 1996). Djavanshir et al. (1996) found *Haloxylon aphyllum*, *Haloxylon persicum*, *Petropyrum euphratica*, and *Tamarix aphylla* as potential species for saline environments in Iranian deserts.

In Central Asia, the native tree *Elaeagnus angustifolia* is salt-tolerant and useful for fruit, fuelwood, gum, leaf fodder, nectar, and honey production and medicinal purposes (see Khamzina et al. 2006). In the Yangiobod farm, northern Tajikistan, an agri-silvicultural trial of trees intercropped with deep-rooted, early maturing, and frost-tolerant legume was established for utilizing degraded, saline lands (Toderich et al. 2013). Soil salinity at root zone was about 45 dS m^{-1}, whereas the groundwater salinity ranged from 8.0 to 16.5 dS m^{-1}. The agroforestry model was characterized by native tree/shrub plantation intercropped between rows with annual halophytes and forage crops on saline marginal lands in the region. The leading tree species with regard to survival rate, growth characteristics, and adaptability to high-saline natural environment included *Haloxylon aphyllum*, *Salsola paletzkiana*, and *S. richteri* followed by *E. angustifolia*, *Populus euphratica*, *P. nigra* var. *pyramidalis*, *Robinia pseudoacacia*, *Morus alba*, and *M. nigra* at saline sandy sites. During the first three years, the growth performance of trees on marginal land was comparable to those reported for trees on irrigated agricultural land (Khamzina et al. 2008). *Tamarix* and *Elaeagnus angustifolia* showed the highest potential for growing on both loamy and sandy soils, which are the dominant soil textures in the region of Central Asia.

About 50% of the irrigated soils in Uzbekistan are affected by varying degrees of salinization due to natural factors and inappropriate land management (Khamzina 2018). The completely abandoned lands undergo further salinization, waterlogging, and fertility loss. However, such lands could be ameliorated by using agri-silvicultural agroforestry involving the creation of small plantations of multipurpose tree species that are tolerant to salinization, waterlogging, and drought (see Khamzina 2018).

Many national and regional projects within the framework of the ICBA-CAT Program show that the cultivation of high-yield, salt-, drought-, and frost-tolerant varieties of cereals, pulses, fodders, and other crops is a very effective measure for the improvement of salt-affected soils in Central Asia and Transcaucasia (Toderich et al. 2018). The various crop species that can be grown on salt-affected clayey and sandy lands include sorghum, African millet, triticale, sesame, quinoa, amaranth, Jerusalem artichoke, globe artichoke, peas, green gram, saltbush (*Atriplex*), and *Kochia* spp. Experiments have been carried out in growing these crop species on arable and livestock farms in Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Azerbaijan for utilizing salt-affected soils, which are otherwise unsuitable for the profitable cultivation of wheat or cotton (see Toderich et al. 2018). African millet is a cost-effective alternative of sorghum and often used as a succession crop in the reclamation of marginal salt-affected lands. Quinoa (*Chenopodium quinoa*), which is highly nutritive, is a multipurpose salt- and drought-tolerant agricultural crop, which has the potential to increase the productivity of marginal lands under conditions of arid climate and shortages of freshwater supply for irrigation (Toderich et al. 2018). While reporting the potential uses of halophytes, Dagar (2018) has mentioned several species such as *Chenopodium album*, *C. quinoa*, *Amaranthus viridis/spinosa*, *Distichlis* spp., *Plantago ovata*, *Portulaca oleracea*, *Beta vulgaris*, *Pennisetum typhoides*, *Salicornia bigelovii*, and *Hordeum vulgare* (as food crops); *Atriplex*, *Kochia*, *Leptochloa*, *Brachiaria*, *Chloris*, *Dichanthium*, *Coix*, *Echinochloa*, *Pennisetum*, *Paspalum*, *Sporobolus*, *Panicum*, and many others (forages); *Vetiveria*, *Pandanus*, *Matricaria*, and *Cymbopogon* (essential and aromatic oils); and *Aloe vera*, *Adhatoda vasica*, *Achyranthes aspera*, *Cassia senna*, *Lepidium sativum*, *Portulaca oleracea*, *Withania somnifera*, *Citrullus colocynthis*, *Catharanthus roseus*, *Glycyrrhiza glabra*, *Calotropis procera*, etc. (medicinal); and many others (see Dagar 2018) are suitable for saline soils or can be cultivated irrigating with saline water and can successfully be grown as agroforestry crops.

There are varying causes of salinization in Ethiopia including irrigation water shortage, deteriorating water quality, and waterlogging, and different solutions to these problems are needed. For example, in highly saline soil conditions, planting salt-tolerant forage grasses (i.e., *Leptochloa fusca*, *Chloris gayana*, *Brachiaria mutica*, *Cynodon dactylon*) and leguminous crops is more practical. In areas where both waterlogging and soil salinity are present, cultivation of trees like *Eucalyptus* hybrid, *Prosopis juliflora*, and *Acacia nilotica* for biodrainage can be useful. Dagar et al. (2016a) have found that clonal *Eucalyptus tereticornis* is the most suitable and economically viable tree along with rice-wheat cropping system in waterlogged areas. When grown on ridges, it could draw down the water table by 85 cm after 3 years of growth and more than 2 m after 5 years of growth. When raised on bunds in 1 m × 1 m space in 66 m apart rows, it could produce 49.5 Mg ha^{-1} dry biomass including 13.4 Mg ha^{-1} root biomass (timber volume 65.4 m^3 ha^{-1}) and sequester about 25 Mg ha^{-1} carbon after 6 years of growth. In block plantations, it could produce 193 Mg ha^{-1} biomass (timber volume 204 m^3 ha^{-1}).

5.5.2 Silvopastoral Agroforestry

Most of the salt-affected soils are suitable for silvopastoral systems across the world. The sodic soils have been reclaimed and utilized by growing salt-tolerant grasses (Malik et al. 1986; Rana and Parkash 1987; Singh and Dagar 2005), protecting natural vegetation cover (Gupta et al. 1990; 2015; Dagar 2014), and adopting reclamation forestry and agroforestry (Singh and Gill 1992; Singh 1995). Using the auger hole planting technique, the integration of trees with naturally growing salt-tolerant grasses was reported to be a viable land use option for improving the biological productivity and fertility of highly sodic soils at Bichhian, northwestern India (Singh and Dagar 2005). The sodic soils are very poor in forage production under open grazing, but with proper management, these can successfully be brought under productive silvopastoral system for sustainable fodder and firewood production. *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana*, *Panicum maximum*, *P. laevifolium*, *P. virgatum*, *P. antidotale*, *P. purpureum*, *Setaria anceps*, and *Sporobolus helvolus* are suitable grasses for developing productive silvopastoral systems. These help in quick bio-reclamation process of these soils. *Vetiveria zizanioides*, *Brachiaria*, *Coix*, *Paspalum*, and *Echinochloa* also tolerate water stagnation and are suitable for waterlogged conditions.

On a highly sodic soil, mesquite (*Prosopis juliflora*) and Kallar grass (*Leptochloa fusca*) silvopastoral practice was found to be promising for firewood and forage production and also for soil amelioration (Singh et al. 1993, 1997; Singh and Dagar 2005). *Leptochloa fusca* grown with *P. juliflora* produced 55.6 to 80.9 Mg ha^{-1} green forage without application of any fertilizer or other amendment (Singh et al. 1993; Singh 1995). In one experiment comprised of *Acacia nilotica* + *Desmostachya bipinnata*, *Dalbergia sissoo* + *Desmostachya bipinnata*, and *Prosopis juliflora* + *Desmostachya bipinnata*, the bole wood (which can be used as small timber) was 4.62–9.78 Mg ha^{-1}, and branch wood biomass (which can be used as fuelwood) production ranged from 4.16 to 20.82 Mg ha $^{-1}$ year $^{-1}$ (Kaur et al. 2002a, Fig. 5.3). The system was found quite effective in improving soil fertility and sequestering carbon. Organic carbon increased by 24–62% in soils under different silvopastoral systems mentioned above as compared to sole grass system. The microbial carbon, as regulated by litter and root carbon input, was found to be good in bio-amelioration of sodic soils (Kaur et al. 2002a, b; Gupta et al. 2015). This system also provided ecosystem co-benefits such as increased soil water-holding capacity, better soil structure, and improved nutrient cycling (Dagar 2014).

Oil-yielding saltbush *Salvadora persica* can perform well both in dry and waterlogged situations in saline soils. *S. persica*-based silvopastoral system has been developed with forage grasses (*Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*) on clay loam saline vertisol (clay 40%, silt 31%, sand 29%; pH ranging from 7.2 to 8.9; ECe from 25 to 70 dS m^{-1}) in Gujarat (Rao et al. 2003). *Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*, when planted on 45-cm-high ridges, could produce 3.17, 1.85, and 1.09 Mg ha^{-1} forage, respectively. When planted in furrows, the forage yield was 3.75, 1.76, and 0.54 Mg ha^{-1} in the case of

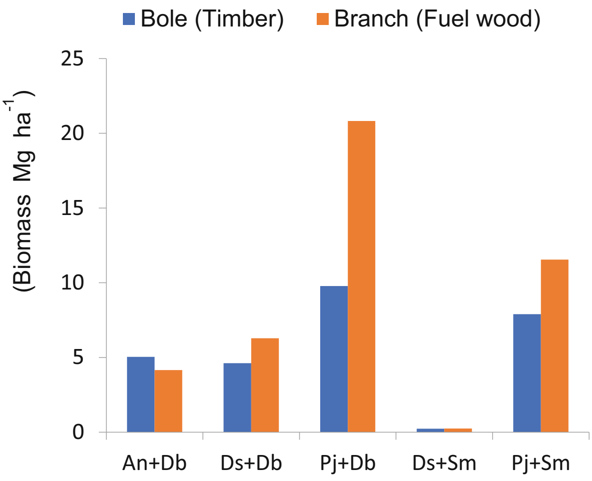


Fig. 5.3 Timber and fuelwood production in silvopastoral systems of *Acacia nilotica* (An), *Dalbergia sissoo* (Ds), and *Prosopis juliflora* (Pj) along with *Desmostachya bipinnata* (Db) and *Sporobolus marginatus* (Sm) after 6 years on a sodic soil at Bichhian, northwestern India (based on Kaur et al. 2002a)

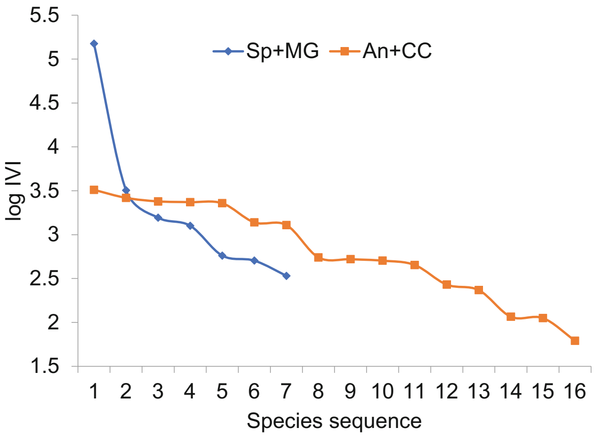


Fig. 5.4 Dominance—diversity curve of herbaceous plants in silvopastoral systems of An + CC (*Acacia nilotica* + *Cenchrus ciliaris*) and Sp + MG (*Salvadora persica* + mixed grasses)

Leptochloa fusca, *Eragrostis* sp., and *Dichanthium annulatum*, respectively, showing their potential for these highly degraded lands. In waterlogged saline areas, several grasses such as *Leptochloa fusca*, species of *Aeluropus*, *Eragrostis*, *Sporobolus*, *Panicum*, *Paspalum, Phragmites*, *Brachiaria*, and *Vetiveria* can successfully be grown along with salt-tolerant trees for viable and sustainable silvopastoral systems to sustain livestock productivity (see Dagar 2014).

The silvopastoral agroforestry systems on calcareous soils under saline water irrigation in dry regions of Haryana are characterized by tree species of *Acacia nilotica* and *Salvadora persica* along with native grasses such as *Cenchrus ciliaris*, *C. setigerus*, *Bothriochloa pertusa*, *Dichanthium annulatum*, and *Panicum miliare*. The diversity curve of herbaceous plants in the *Acacia nilotica* system showed a log-normal distribution of species (Fig. 5.4). In the case of *Salvadora persica* system, the diversity curve of herbaceous plant species was initially slightly steep and then showed a log-normal distribution (Fig. 5.4). The dominance diversity curves describe the patterns of the way in which species of high importance and intermediate importance and rare species are assembled in a community (Whittaker 1965).

According to Kumari et al. (2018), the aboveground biomass of trees for the *Acacia nilotica* silvopastoral systems was 203.16 Mg ha^{-1}, and the belowground biomass was 37.88 Mg ha^{-1} (Table 5.3). For *Salvadora persica* system, the plant biomass was as follows: the aboveground biomass was 244.54, and the belowground biomass was 44.58 Mg ha^{-1}. Total biomass carbon pool in trees varied in accordance with tree biomass of *Acacia nilotica* and *Salvadora persica*. Total carbon stock (Mg ha^{-1}) in the two silvopastoral systems was 120.92 for *Acacia nilotica* + *Cenchrus ciliaris* system and 144.56 for *Salvadora persica* + mixed grass system.

Qureshi et al. (1993a, b) reported that saltbushes *Atriplex amnicola*, *A undulata*, and *A. lentiformis* were among the most successful forages in Pakistan producing dry biomass up to 8 Mg ha^{-1}. These bushes along with grasses such as *Leptochloa fusca*, *Brachiaria ramosa*, *Aeluropus lagopoides*, *Sporobolus helvolus*, *Dichanthium annulatum*, *Dactyloctenium aegyptium*, *Panicum maximum*, *Digitaria ciliaris*, and *Cynodon dactylon* are suitable along with *Eucalyptus camaldulensis* trees. *L. fusca* grass had special advantage of ameliorating soil at rapid rate. Ismail et al. (2019) reported that *Acacia ampliceps* is a successful tree along with grasses such as *Paspalum vaginatum*, *Sporobolus virginicus*, and *S. arabicus* in the dry ecology of United Arab Emirates, when irrigated with saline water. They also established successfully *Salicornia bigelovii* (seed oil crop) and species of *Atriplex* (*halimus*, *amnicola*, *nummularia*, *canescens*, *lentiformis*) and *Kochia scoparia* as fodder crop in these habitats. *Pennisetum typhoides* has been found a suitable coarse grain and fodder crop for dry ecologies and can be cultivated using saline and sewage waters. Species of *Atriplex*, *Salsola*, *Haloxylon*, and *Salvadora* are prominent forage shrubs of saline soils distributed widely and relished by camel, sheep, and goats.

Toderich et al. (2009) have discussed the possibility of introducing livestock-based farming system under desert saline conditions in Kyzylkum in Central Asia. According to these workers, *Alhagi pseudalhagi*, grass species, and *Artemisia diffusa* (containing minimum concentration of mineral ions) were found to be palatable and valuable feed for livestock. Planting herbaceous fodder crops between fodder shrubs on intensive agroforestry plantations could be useful to feed Karakul sheep in sandy desert areas degraded by both overgrazing and salinity. The wild halophyte species planted in widely spaced patterns (15–25 m) facilitated easy mechanical cultivation and harvesting of grass and cereals. The fodder shrubs were integrated with cereal farming system, including rangeland species alone, or mixed with different salt-tolerant traditional fodder crops, such as *Sorghum bicolor* and *Pennisetum glaucum*. Fodder production of some of native halophytes mixed with different promising salt-tolerant crops traditionally growing under irrigation with mineralized artesian water at the Kyzylkum site in Central Asia is given in Table 5.4. The fodder production ranging from 1.0 to 3.46 Mg ha^{-1} was significant for *K. prostrata*, *Atriplex canescens*, *Alhagi pseudalhagi*, and *Glycyrrhiza glabra*

Table 5.3 Aboveground and belowground biomass and carbon stock in *Acacia nilotica* and *Salvadora persica* silvopastoral systems on calcareous soil at Hisar

	Abovegroundbiomass (Mg ha^{-1})	Belowground biomass (Mg ha^{-1})	Aboveground carbon stock (Mg ha^{-1})	Belowground carbon stock (Mg ha^{-1})	Total carbon stock (Mg ha^{-1})
Acacia nilotica + *Cenchrus ciliaris* system	203.16	37.88	101.58	18.94	120.52
Salvadora persica + mixed grass system	244.54	44.58	122.27	22.39	144.56
Natural grassland	2.56	–	1.28	–	1.28

Table 5.4 Fodder production of some perennial halophytic pastures at the Kyzylkum site in Central Asia

Plant species	Fodder production (Mg ha $^{-1}$)
Salsola orientalis	1.0–2.2
Kochia prostrata	2.06–2.16
Atriplex canescens	2.05–2.25
Agropyron desertorum	0.40–0.60
Alhagi pseudalhagi	1.24–1.60
Glycyrrhiza glabra	1.27–3.46

Source: Toderich et al. (2009)

(Toderich et al. 2009). *Kochia scoparia* and *Agropyron desertorum are found to* produce up to 1.3 Mg DM ha^{-1} in association with wild growing *Alhagi pseudalhagi*. Wild native halophytes showed low ion contents and could be recognized as alternative forages, both in pure halophytic pastures and in mixed grass stands.

Salt-tolerant tree species such as species of *Populus*, *Haloxylon*, *Salix*, *Elaeagnus*, and *Morus* and shrubs species such as *Atriplex*, *Berberis*, and *Hippophae rhamnoides* have good potential as part of the arid fodder production system on good deep soils (Toderich et al. 2009). The incorporation of fodder halophytes into the agri-silvopastoral system represents low-cost strategies for rehabilitation of desert degraded rangelands and abandoned farmer lands affected both by soil and water salinity in regions of Central Asia (Toderich et al. 2013).

Barrett-Lennard (2003) gave an extensive account of salt land pastures in Australia. He emphasized that samphire (*Halosarcia pergranulata*, *H. lepidosperma*, *H. indica* subsp. *bideris*), bluebush (*Maireana brevifolia*), and saltbushes (*Atriplex* spp.) are a group of highly salt-tolerant succulent perennial shrubs, which could be grown on waterlogged salt land pastures in Australia. *H. pergranulata* contains about 14% crude protein on oven-dry biomass basis and is better suited to sheep grazing. *Cornus stolonifera*, *Celtis occidentalis*, *Cephalanthus occidentalis*, *Populus deltoides*, *Acer saccharinum*, and *Quercus australis* and species of *Alnus* and *Salix* are among woody species reported to be prominent as part of silvopastoral systems in Australia (Mitchell and Wilcox 1994).

In recent years, in search of potential halophytic crops, work is in progress across the globe in a number of countries having problems of salinity. These include Australia, Bahrain, Bangladesh, Belgium, Brazil, Canada, China, Egypt, France, Germany, India, Iran, Israel, Italy, Japan, Kenya, Kuwait, Mexico, Morocco, Pakistan, Puerto Rico, Russia, Saudi Arabia, Senegal, Sri Lanka, Switzerland, the United Kingdom, the United States, and Venezuela. Based on the research carried out in these countries, some of the potential halophytic genera including trees, shrubs, and herbaceous species have been identified which include *Acacia*, *Achras*, *Adhatoda*, *Agropyron*, *Aloe*, *Amaranthus*, *Anacardium*, *Andropogon*, *Anethum*, *Arthrocnemum*, *Atriplex*, *Avicennia*, *Batis*, *Brachiaria*, *Bruguera*, *Calophyllum*, *Capparis*, *Carandas*, *Carissa*, *Cassia*, *Casuarina*, *Catharanthus*, *Cenchrus*, *Ceriops*, *Chenopodium*, *Chloris*, *Citrullus*, *Coccoloba*, *Coix*, *Cordia*, *Cressa,* *Crithmum*, *Cymbopogon*, *Distichlis*, *Eucalyptus*, *Feronia*, *Glycyrrhiza*, *Grindelia*, *Halosarcia*, *Juncus*, *Kochia*, *Kosteletzkya*, *Lepidium*, *Leptochloa*, *Leucaena*, *Limonium*, *Lumnitzera*, *Maireana*, *Matricaria*, *Nypa*, *Ocimum*, *Pandanus*, *Panicum, Paspalum*, *Pennisetum*, *Plantago*, *Pongamia*, *Porterasia*, *Portulaca*, *Prosopis*, *Rhizophora*, *Salicornia*, *Salvadora*, *Simmondsia*, *Sonneratia*, *Spergularia*, *Sporobolus*, *Suaeda*, *Tamarix*, *Thinopyrum*, *Vetiveria*, *Vigna*, *Withania*, *Xanthium*, *Xylocarpus*, *Ziziphus*, and *Zostera* to name a few.

5.5.3 Fruit-Based Agroforestry Systems

Being more economically viable, fruit-based cropping system is more acceptable to the farmers. Experiments at Narendra Deva University of Agriculture and Technology, Faizabad, and CSSRI, Karnal, northwestern India, have shown that there are about half dozen fruit plants that can be grown in alkali soils by adopting proper site preparation techniques and by using appropriate doses of organic and inorganic amendments. The fruit species such as guava (*Psidium guajava*), karonda (*Carissa carandas*), pomegranate (*Punica granatum*, which does not tolerate stagnation of water), ber (*Ziziphus mauritiana*), gooseberry (*Emblica officinalis*), bael (*Aegle marmelos*, water stagnation sensitive), sapota (*Achras zapota*, frost sensitive), jamun (*Syzygium cumini*), tamarind (*Tamarindus indica*), and Kaith (*Feronia limonia*) are suitable for moderate alkali soils and can be grown in wider spaces along crops. An experiment in semi-reclaimed alkali soil at Sivri farm near Lucknow, northern India, indicated that gooseberry (amla), karonda, *Syzygium cumini*, *Psidium guajava*, *Ziziphus mauritiana*, and *Punica granatum* were the most promising fruit trees. These fruit trees are sodicity tolerant but do not tolerate water stagnation and frost (Dagar et al. 2001b). Tomar et al. (2004) cultivated *Leptochloa fusca* fodder grass (10.6–16.7 Mg ha^{-1} forage), wheat (1.6–3.2 Mg ha^{-1}), onion (2.3–4.0 Mg ha^{-1}), and garlic (2.3–4.1 Mg ha^{-1}) as intercrops among these fruit trees. Further, Dagar et al. (2016d) developed fruit tree-based agroforestry system successfully in sandy loam calcareous soils in northwestern India by growing fruits of dry region such as karonda (*Carissa carandas*), gooseberry (*Emblica officinalis*), and bael (*Aegle marmelos*) along with field crops such as barley (*Hordeum vulgare*) and mustard (*Brassica juncea* cv. CS 54, CS 56; seed oil) in winter and pearl millet (*Pennisetum typhoides*; coarse grain and fodder) and cluster bean (*Cyamopsis tetragonoloba*; for gum) during rainy season irrigating with saline water of ECe 8–10 dS m^{-1}. The fruit trees were successfully grown in the sill of furrows used for irrigation (Fig. 5.5). Saline water could be used for establishing these fruit trees and irrigating the component crops without significant salinity buildup. Other successful fruit trees of the region include ber (*Ziziphus mauritiana*), pomegranate (*Punica granatum*), kair (*Capparis decidua*, for pickle), lasura (*Cordia rothii*, for pickle), and Kaith (*Feronia limonia*) which can be grown using saline water (Dagar et al. 2008). On the basis of a long-term study, it was found that the fruit-based agroforestry systems could be successfully established with saline groundwater irrigation for supporting sustainable crop and fruit production.

Fig. 5.5 Barley (*Hordeum vulgare*) cultivated as intercrop with karonda (*Carissa carandas*) using saline water for irrigation (Source: Dagar JC, personal)

Dill (*Anethum graveolens*), Tara-mira (*Eruca sativum*), periwinkle (*Catharanthus roseus*), castor (*Ricinus communis*), jojoba (*Simmondsia chinensis*), and sesame (*Sesamum indicum*) were among other valuable nonconventional crops which could be cultivated with saline irrigation (ECe 8–12 dS m^{-1}) in isolation as well as agroforestry crops on degraded calcareous soils (Dagar et al. 2005, 2008, 2013; Tomar et al. 2010). *Euphorbia antisyphilitica*, a succulent laticiferous shrub, commonly known as candelilla and wax plant, was found to be a potential hydrocarbon-yielding petro-crop (Dagar et al. 2012). It yields 8–10% biofuel of the total biomass. It produced about 23 Mg ha^{-1} dry biomass after 2 years of growth, when irrigated with saline water. It is a low-nutrient and low-water-requiring plant and thrives well on degraded calcareous soils (Dagar et al. 2012). Edible cactus (*Opuntia ficus-indica*), which is also medicinal, performed well on degraded lands in dry regions and could be established using saline water for irrigation (Gajender et al. 2013, 2014). *Chrysanthemum indicum*, *Clandulla*, *Matricaria chamomilla*, and *Catharanthus roseus* were among the medicinal and flower-yielding species which could be cultivated successfully irrigating with saline water up to ECe 6 dS m^{-1}.

5.5.4 Agroforestry Systems Based on Medicinal and Aromatic Crops

Some aromatic grasses such as palmarosa (*Cymbopogon martinii*) and lemon grass (*C. flexuosus*) can be cultivated successfully on moderate alkali soils up to pH 9.2, while *Vetiveria zizanioides* could withstand both high pH and stagnation of water (Dagar et al. 2004, 2006a, b). *Plantago ovata*, a short duration crop, produced 1.47–1.58 Mg ha^{-1} unhusked grain at pH 9.2 and 1.03–1.12 Mg ha^{-1} at pH 9.6

showing its potential for utilizing moderate alkali soil (Dagar et al. 2006a, b). Many cultivars of *Ocimum* withstand moderate alkali soil. *Matricaria chamomilla*, *Catharanthus roseus*, and *Chrysanthemum indicum* were other interesting medicinal and flower-yielding plants which could be grown on moderate alkali soil (Dagar et al. 2009a, b). All these medicinal plants can be integrated suitably as intercrops in agroforestry systems either with forest trees or fruit trees on moderate alkali soils.

Dagar et al. (2015) reported that liquorice (*Glycyrrhiza glabra*), a leguminous crop, could successfully be grown on alkali soils with pH ranging from 8.4 to 9.8. The forage yield was 2.4–6.1 Mg ha^{-1} per year; root (medicinal and highly remunerative) biomass ranged from 6.0 to 7.9 Mg ha^{-1} after 3 years of growth. The sodic lands under this crop were reclaimed considerably in terms of reducing soil pH and exchangeable sodium percentage and increasing organic carbon by growing liquorice (Dagar et al. 2015). This also withstands waterlogging.

In the Hungary Steppes in Uzbekistan, the highly saline abandoned soils were restored by growing licorice (*Glycyrrhiza glabra*), which is known to be a salt-tolerant perennial shrub species (Kushiev et al. 2005). It was grown on a 13 ha field that had been abandoned due to high levels of salts and shallow groundwater; an adjacent field of 10 ha served as the control during the study period, 1999–2003. Comparing the average yields of wheat and cotton in the study area as 1.75 and 1.5 Mg ha^{-1}, respectively, liquorice showed the potential to increase productivity and farm-level income from abandoned saline fields because of lowering of the water table, enhancement of the leaching of salts, as well as increase in the soil organic carbon content (Kushiev et al. 2005). *Aloe vera*, *Adhatoda vasica*, *Achyranthes aspera*, *Asparagus racemosus*, lemon grass (*Cymbopogon flexuosus*), palma rosa (*C. martinii*), vetiver (*Vetiveria zizanioides*), psyllium (*Plantago ovata*), *Lepidium sativum*, *Cassia senna*, *Matricaria chamomilla*, and *Catharanthus roseus* were among other valuable nonconventional medicinal crops which could be cultivated on degraded calcareous soils with saline irrigation (ECe 8–12 dS m^{-1}) in isolation and as agroforestry crops (Dagar et al. 2005, 2008, 2013, 2015; Tomar et al. 2010).

5.5.5 Energy Plantation

Among the biofuel and bioenergy plant species, Jatropha (*Jatropha curcas*) and Karanj (*Pongamia pinnata*) are considered to have excellent potential to produce alternative fuel for compression ignition engines. *Jatropha curcas* is believed to be native of Mexico and Central America but is commonly found throughout most of the tropical and subtropical regions of the world. It has been found to improve soil fertility and decrease soil sodicity after 6 years of its growth at Banthra Research Station, Lucknow (Singh et al. 2013). *Pongamia pinnata* also grows well on moderate alkali soils and saline regions in southern India. Species of *Prosopis* such as *P. juliflora*, *P. alba*, *P. articulata*, *P. levigata*, and *P. nigra* could produce high biomass in highly alkali soil. *Tamarix articulata* also produces high biomass, particularly on moderate saline and sodic soils. *Casuarina* also thrives well on salty soils in southern parts of the country and is a boon along sandy beaches in coastal areas. All these can successfully be used as energy plantations and even in gassy fires to generate electricity in rural employment programs (Dagar et al. 2001b; Singh and Dagar 2005; Dagar 2014).

5.5.6 Agroforestry for Dryland Salinity

Alley cropping is a type of agroforestry system where crops are grown in the alleys between spaced rows of trees or shrubs. Alley cropping and parkland agroforestry were suggested as a means of increasing water use in the agricultural landscape as well as managing dryland salinity (Lefroy et al. 1992; Lefroy and Scott 1994). A special feature of many dryland soils is salinity, either through natural occurrence or increasingly as a result of irrigation (Glenn et al. 1992). Many halophytic plants are especially adapted to these conditions, and there is large potential for sequestering carbon by these plants in saline soils. The halophytes can be used as food, forage, feed, and oilseed (Glenn et al. 1992; Shahid et al. 2013a; Dagar 2018), and many of these help in amelioration of soil as these absorb a lot of salt, which is harvested along with their biomass. Many tree species are reported to use water with an ECe of 5–8 dS m^{-1}, and some more salt-tolerant species are capable of using substantial amounts of saline groundwater (ECe up to 16–20 dSm^{-1}) (Marcar and Crawford 2004, Table 5.5). The choice of plant species also depends on local climate, soil type, and other purposes of the planting. Alley-farming configurations have been used on sandy soils in western Australia, with trees planted in narrow belts over extensive areas, interspersed with annual or perennial pastures or crops.

Many types of dryland salinity can be controlled by reintroducing trees and other deep-rooted vegetation into agricultural landscapes, to restore a hydrological balance. Trees and shrubs can be used to reduce groundwater recharge and to reduce saline or potentially saline groundwater levels through roots. Stirzaker and Lefroy (1997) have compiled information on alley farming in Australia. In the medium to low rainfall areas in western Australia, some 5000 ha of the land has been planted to

Table 5.5 Tree species for controlling dryland salinity in Australia (compiled from Marcar and Crawford 2004)

Nonsaline and low-salinity areas (soil ECe < 4 dS m^{-1})	Moderately saline areas (ECe 4–8 dS m^{-1})	Highly saline areas (ECe 8–16 dS m^{-1})
On well-drained sites – Spotted gums (*Corymbia* species), ironbarks (e.g., *E. sideroxylon* and *E. tricarpa*), southern blue gums (*E. globulus* subsp. *bicostata*), sugar gum (*E. cladocalyx*)	Tree species *Casuarina cunninghamiana*, *E. argophloia*, *E. camaldulensis*, *E. melliodora*, *E. moluccana*, possibly *E. sideroxylon*, *E. tereticornis*,	*E. occidentalis* and *Casuarina glauca*, some provenances of *E. camaldulensis*
Areas of poorer drainage—*E. botryoides*, *E. microcarpa*, *E. saligna*, *E. viminalis*, *Pinus brutia*	Some shrub species of *Acacia* and *Melaleuca* are able to tolerate moderate salinity	Very salt-tolerant species, *Casuarina obesa*, *Acacia stenophylla*

control dryland salinity and rising water tables in the wheat belt (Stirzaker and Lefroy 1997). A mixture of salt-tolerant species of the genera *Eucalyptus*, *Acacia*, *Casuarina*, and *Atriplex* has been used in and around Narrogin and Katanning in the 400 to 500 mm rainfall zone. The best documented example of saline alley farming has been cited from the Boundain property of Graeme Wilson, near Narrogin, annual rainfall of the region being about 500 mm; water tables ranged from 1 to 3 metres belowground, and salinity was 500 to 3000 mS m^{-1} (Stirzaker and Lefroy 1997). The alley farming systems were characterized by salt-tolerant trees including the swamp oak (*Casuarina obesa*), flat-topped yate (*Eucalyptus occidentalis*), Salt River gum (*E. sargentii*), York gum (*E. loxophleba*), Kondinin blackbutt (*E. kondininensis*), river red gum (*E. camaldulensis*), and swamp mallet (*E. spathulata*). The trees were planted at a distance of 5 metres in single rows at 25 and 12.5 metre alley widths, resulting in tree densities of 80 and 160 stems per hectare, respectively. Water table monitoring bores were placed in the alley farming areas and in an adjacent bare area without trees. It was shown that water table drawdown in the alleys began in the fourth year after planting of the trees. Sub-clover was successfully re-established in 1986 following leaching of salts from the soil surface and lowering of groundwater. However, the growth of pasture was adversely affected due to strong competition of trees with the pasture for resources after 4 years ((Stirzaker and Lefroy 1997).

Plants may be used to reduce saline or potentially saline groundwater levels through roots that directly access the water table and increase the discharge through transpiration by plants (Johnson et al. 2009). For highly saline areas (ECe 8–16 dS m^{-1}) in Australia, only a few tree species such as *Eucalyptus occidentalis* and *Casuarina glauca* were found to be suitable. For extremely saline areas (ECe over 16 dS m^{-1}), *Casuarina obesa*, *Acacia stenophylla*, a few Melaleucas, and some widely spaced saltbush could be appropriate for highly saline areas (Johnson et al. 2009). Barrett-Lennard (2003) has given an illustrated account of pasture development in waterlogged saline areas of Australia, which may be consulted for more details.

The seed of samphire (*Salicornia bigelovii*) contains high-quality unsaturated oil (30%) and proteins (40%) and can also be used to make biodiesel and as animal feed. Five different lines of *S. bigelovii* were evaluated successfully using saline water for irrigation in International Center for Biosaline Agriculture (ICBA) (Shahid et al. 2013b), and this can even be grown in hypersaline drainage water (Grattan et al. 2008). The BEHAR (Arabian Saline Water Technology Company Limited) of Saudi Arabia had been working on different halophytic species and developed many *Salicornia* lines suitable for vegetable, fodder, and oilseed purposes. Line R12 was found most superior in terms of plant height, biomass, and seed weight in UAE conditions (Shahid et al. 2013b).

Tomar et al. (2003a, b, 2005), Dagar et al. (2008, 2013, 2016d), Yadav and Dagar (2016), and Dagar and Yadav (2017) have evaluated more than three dozen tree species and several forage grasses and nonconventional crops of high value and established forest and fruit-tree-based agroforestry systems on degraded calcareous soils irrigated with water with an ECe of 8–12 dS m^{-1} in dry regions of western

India (annual rainfall <500 mm) as discussed earlier in this text. These studies indicate that with judicious management of saline aquifers of dry region, the degraded lands can successfully be utilized for sustainable production and livelihood security.

5.5.7 Halophytes for Phytoremediation

There is great potential of growing halophytes for food products for local people, animal fodders, biofuel, and a remedy for restoration of highly saline soils (Toderich et al. 2018; Dagar 2018). Boyko (1966) suggested that halophytes could be used to desalinate soil and water. The hyper-accumulating halophytic species such as *Suaeda maritima*, *S. portulacastrum*, *S. fruticosa*, *S. salsa*, *S. calceoliformis*, *Kalidium folium*, *Salsola baryosma*, *Sesuvium portulacastrum*, *Arthrocnemum indicum*, *Atriplex nummularia*, and *A. prostrata* have been found to accumulate high concentrations of salt in their aboveground tissues that can improve saline soils by harvesting the plants on a regular basis (Zhao 1991; Ravindran et al. 2007; Manousaki and Kalogerakis 2011).

Planting and sowing salt-resistant plants in combination with agrotechnical and engineering measures encourages their gradual desalinization and a gradual improvement of their properties on salt-affected soils in Ukraine (Truskavetsky and Tkach 2018). The main agrotechnical and ameliorative measures practiced in agroforestry on salt-affected soils include deep plowing, wide spacing, using salt-tolerant species, and careful management of soils and plantations. Some promising plant species include *Suaeda arcuata*, *S. acuminata*, *Atriplex cana*, *A. canescens*, *Climacoptera crassa*, *Bassia hyssopifolia*, *Salicornia herbacea*, *Kochia scoparia*, *Glycyrrhiza glabra*, *Artemisia halodendron*, etc. The presence of carbonates ($MgCO_3$) and chlorides in soil solution affects the growth of different tree and shrub species (Truskavetsky and Tkach 2018). The tree and shrub species growing on soils containing different salt concentrations are given in Table 5.6.

Liquorice (*Glycyrrhiza glabra*), known for its medicinal properties and nutritional value, is considered to be a promising ameliorator for the successful

Table 5.6 The tree and shrub species growing on soils containing different salt concentrations in Ukraine (Truskavetsky and Tkach 2018)

	Tree species	Shrub species
Salt-tolerant species	*Tamarix ramosissima, T. tetrandra, and T. pallasii*	
Strongly salt-resistant species	*Elaeagnus angustifolia*	*Lonicera tatarica*, *Ribes aureum*, and *Cornus sanguinea*
Salt-resistant species: In forest steppe and true steppe	*Quercus robur*, *Pyrus pyraster*, *Acer campestre*, *A. tataricum*, *Ulmus laevis*, and *Thuja* sp.	*Crataegus* spp. and *Rhamnus cathartica*; in dry steppe – *Robinia pseudoacacia*, *Gleditsia* sp., *Ailanthus* sp., *Styphnolobium japonicum*, *Fraxinus angustifolia*

reclamation of irrigated saline soils. On an average, it yields of 6–8 Mg ha^{-1} in hay and 8–10 Mg ha^{-1} in root (valuable raw material for pharmaceutical and food industries) on irrigated saline soils with a shallow groundwater table in the Syr Darya Region and Central Kyzylkum (Kushiev et al. 2005). *Atriplex* species have been successfully used in the reclamation of gypsum-containing and alkaline soils in the southwest of Kazakhstan. Many *Atriplex* species can also be used as a fuel by local people.

Toderich et al. (2018) reported that the most successful halophyte species that can be grown on salt-affected soils and used as winter fodders for farm animals include *Atriplex nitens*, *Climacoptera lanata*, species of *Kochia*, *Salsola*, *Aellenia*, *Haloxylon*, *Artemisia*, *Ceratoides*, *Suaeda*, *Glycyrrhiza*, etc. The dry matter yields of fodder crops harvested from newly created halophyte plantations can vary from 1.2 to 1.5 Mg ha^{-1} depending on the local environmental conditions and plant species composition. For utilization of halophytes, please see Dagar (2018).

5.5.8 Agroforestry for Waterlogged Areas

Waterlogging may be defined as stagnation of water on the land surface or where the water table rises to an extent that soil pores in the crop root zone (0 to 3 m from surface) become saturated, resulting in restriction in normal circulation of air leading to decline in the level of oxygen and increase in the level of carbon dioxide (Heuperman et al. 2002; Setter et al. 2009). Much of the world's saline land is also subject to waterlogging (saturation of the soil) because of the presence of shallow water tables or decreased infiltration of surface water due to sodicity (Ghassemi et al. 1995; Qureshi and Barrett-Lennard 1998). Waterlogged land can be brought under cultivation by planting trees with high transpiring rate. These bio-drain the root-zone water into the atmosphere by the process of absorption (through roots), translocation (through xylem), and transpiration (through stomata of leaves), and the process is known as biodrainage. It may be defined as "pumping of excess soil water by deep-rooted plants using their bio-energy" (Jeet-Ram et al. 2008). The *Eucalyptus*-based agroforestry on waterlogged soils has been developed in semiarid regions of Haryana (Jeet-Ram et al. 2007; Kumar 2012; Dagar et al. 2016a). Dagar et al. (2016a) reported timber and fuelwood biomass in clonal *Eucalyptus tereticornis* plantation in different spacing in shallow water-table areas at Puthi, Hisar. After 6 years, total dry biomass production of 49.5 Mg ha^{-1} was obtained from row plantation (1 m × 1 m space) on acre line and 193 Mg ha^{-1} in block plantation (2 m × 4 m space) showing potential of clonal *Eucalyptus* on waterlogged farmlands. The total carbon sequestered in 1 m × 1 m space was 22.8, and in block plantations, the total carbon sequestered was 90.6 Mg ha^{-1} (Table 5.7).

Biomass accumulation was studied in farmer's plantation model of biodrainage in northwestern India (Toky et al. 2011). An abandoned waterlogged area (water table up to 2 m) on a farm adjacent to Balsamand canal at HAU Hisar, India, was planted with ten tree species. After 6 years of establishment of the plantations, the cone of depression of the water table beneath the plantation strips was observed, the decline

Table 5.7 Bole and branch wood biomass in clonal *Eucalyptus tereticornis* plantation in different spacing in shallow water-table areas after 4 years at Puthi in Haryana (based on Dagar et al. 2016b)

Tree spacing	Components	Biomass (Mg ha^{-1})	C sequestration
1 m × 1 m (300 tree ha^{-1})	Bole (timber)	33.5	15.2
	Branches and leaves (firewood)	2.6	1.1
	Roots	13.4	6.5
1 m × 2 m (150 trees ha^{-1})	Bole	19.1	8.9
	Branches and leaves	1.6	0.7
	Roots	8.0	3.9
1 m × 3 m (100 trees ha^{-1})	Bole	13.5	6.4
	Branches and leaves	1.1	0.5
	Roots	5.4	2.6
Block (2 m × 4 m) (1250 trees)	Bole	141.7	66.5
	Branches and leaves	9.8	4.2
	Roots	41.4	19.9

in water table was found to be 20 cm over the entire area (Toky et al. 2011). The aboveground and belowground biomass accumulation after 6 years was greater in different clones of *Eucalyptus tereticornis* (102 to 186 Mg ha^{-1}) as compared to other tree species (12 to 95 Mg ha^{-1}).

Khamzina et al. (2006) evaluated the potential of nine multipurpose tree species to reduce saline ground water tables in the lower Amu Darya River region of Uzbekistan. On the basis of water use characteristics, salinity tolerance, growth rate, and the ability to produce fodder and fuelwood, *Elaeagnus angustifolia* performed best for biodrainage; *Populus* spp. and *Ulmus pumila* also showed good potential for biodrainage (Khamzina et al. 2006). The fruit species in the region such as *P. armeniaca* and *Morus alba* showed low biodrainage potential. We convinced a farmer to grow gooseberry (*Emblica officinalis*), known for dry region, in waterlogged areas and found that it performed excellent in its vegetative stage, but unfortunately, the farmer harvested it before it came to bearings. Licorice (*Glycyrrhiza glabra*), a medicinal (root used in medicine) legume crop, was found growing well in waterlogged situation.

5.6 Soil Enrichment and Bio-Amelioration Through Agroforestry

Soil improvement in agroforestry systems is linked to biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, buildup of soil organic matter from aboveground and belowground parts of plants, increase in soil microbial activity, improvement in soil enzyme activity, and the enhanced activity of arbuscular mycorrhizal fungi. Soil microbial biomass is an important component of soil organic matter comprising 1–3% of total soil organic matter (Jenkinson and

Ladd 1981). It is a labile fraction of soil organic matter and conserves nutrients for plant growth (Singh et al. 1989). Mycorrhizal fungi could sequester increased amounts of C in living, dead, and residual hyphal biomass in the soil and may play a key role in soil carbon sequestration (Treseder and Allen 2000). Some cross observations have already been mentioned in running text, and specific aspects are discussed below.

5.6.1 Improvement in Soil Properties

Revegetation of sodic wastelands in western Uttar Pradesh in India is reported to ameliorate soil conditions and improve soil biological activity (Tripathi and Singh 2005). After 40 years, the rehabilitated new forests caused significant soil amelioration of sodic soil in the Indo-Gangetic plains (Tripathi and Singh 2005). In these rehabilitated new forests, the soil amelioration was greatest in terms of total N, mineralized N, available N, and soil organic carbon. There was also significant reduction in exchangeable sodium percentage of the rehabilitated soils. Dagar et al. (2001b) and Singh and Dagar (2005) reported that *Prosopis juliflora*, *Tamarix articulata*, and *Acacia nilotica* trees ameliorated highly sodic soil in terms of reduction in pH and ESP values, and after 7 years of growth, the organic carbon increased in upper 15 cm soil by 0.26, 0.24, and 0.10% in respective species. Similar results were obtained by Singh et al. (2008) after 10 years of study in Uttar Pradesh in India where besides above species *Pongamia pinnata*, *Casuarina equisetifolia*, *Prosopis alba*, and *Terminalia arjuna* accumulated from 3.3 to 4.3 g kg^{-1}organic carbon in soil. Khan and Khan (2003) reported the performance of ten tree species (*Azadirachta indica*, *Dalbergia sissoo*, *Albizia procera*, *Terminalia arjuna*, *Eucalyptus* hybrid, *Leucaena leucocephala*, *Acacia catechu*, *A. nilotica*, *Morus alba*, and *Cassia siamea*) planted on highly sodic soil (pH 10.5) in Uttar Pradesh in India in geometry of 4 m × 4 m (first four trees) or 4 m × 2 m (the rest of the trees). Arable crops (rice-wheat) were cultivated in interspaces. After 10 years, soil pH was reduced to 7.3 to 8.4 under different trees (average soil pH 8.2) showing the potentials of bio-reclamation by tree plantations. At the age of 14 years, the quantity of litter varied from 5.0 Mg ha^{-1} in *T. arjuna* to 12.5 Mg ha^{-1} in *Cassia siamea*. The quantity of litter was more than 10 Mg ha^{-1} in *A. procera*, *L. leucocephala*, *A. catechu*, and *A. nilotica*. Singh and Gill (1992) reported increase in organic carbon under *P. juliflora*, *T. arjuna*, *A. nilotica*, *Eucalyptus tereticornis*, and *Albizia lebbeck* after 20 years of growth to 0.93, 0.86, 0.85, 0.66, and 0.62%, respectively, from initial 0.22%.

Kallar grass (*Leptochloa fusca*)-*Prosopis juliflora* silvopastoral system has been found most effective in soil amelioration of sodic soils (Singh et al. 1993; Singh and Dagar 2005). A nitrogen-fixing bacterium *Azoarcus* is associated with roots of Kallar grass, and plant nitrogen of 90–120 kg $^{ha-1}$ is derived from associated fixed nitrogen (Malik et al. 1986). The system could improve the soil to the extent that after 4 and a half years less-tolerant but more palatable species of fodder such as Persian clover (*Trifolium resupinatum*), Egyptian clover (*T. alexandrinum*), lucerene

(*Medicago sativa*), and sweet clover (*Melilotus denticulatum*) could be grown successfully with *P. juliflora* and the system could ameliorate the soil for normal crops in ten years of time. In silvopasture agroforestry systems at Bichhian, northwestern India, there was large input of plant residue both from aboveground and belowground parts of trees and grasses into the soil resulting in the improvement of soil properties and fertility of highly sodic soils (Kaur et al. 2002a; Singh and Dagar 2005). In saline vertisols, grasses such as *L. fusca*, *Brachiaria mutica*, and *Vetiveria zizanioides* in 3 years could remove 144.8, 200.0, and 63.5 kg ha^{-1} sodium from soil, respectively (AICRP 2000–2004). The energy plantation of *Jatropha curcas* after 6 years of its growth at Banthra Research Station, Lucknow, northern India, has been found to improve various soil properties like soil bulk density, pH, electrical conductivity (ECe), and exchangeable sodium percentage (ESP) which decreased due to growth of plants in energy plantation.

Rao and Gill (1995) tried the nitrogen-fixing potentials of different accessions of *Sesbania* and found it to be a quite potential source of nitrogen fixation in moderate alkali soils contributing to 105–150 kg nitrogen per hectare. At 100 days of growth, a biomass of about 31 Mg ha^{-1} could be obtained, and the biofertilizer value in leaf and tender stems was 125, 5, 81, and 12 kg ha^{-1} of N, P, K, and S, respectively. They also found pigeon pea (*Cajanus cajan*) and *Sesbania sesban* as suitable species having soil amelioration properties. *C. cajan* could produce 9.1 Mg ha^{-1} dry biomass (used as firewood) and 2 Mg ha^{-1} litterfall, which led to the recycling of 39.5, 2.1, 7.3, and 2.1 kg ha^{-1} of N, P, K, and S, respectively, to the benefit of the next crop in rotation, and 115 kg ha^{-1} N was fixed in growing season. In *Sesbania sesban*, the N accumulation in aerial and root parts was observed to be 449 and 102 kg ha^{-1}, and in high density plantation managed by coppicing for 6 years, the N fixation was 350 kg ha^{-1} $yr.^{-1}$ in the first 3 years and 170–240 kg ha^{-1} $yr.^{-1}$ in the next 3 years. As stated earlier, agroforestry is an environment-friendly tool (biodrainage) for combating waterlogging in canal command areas. Now, it is an established fact that *Eucalyptus*-based system is quite remunerative and successful for waterlogged areas. Besides *Eucalyptus*, species of *Acacia*, *Populus*, *Pongamia*, *Casuarina*, *Terminalia*, *Syzygium*, and *Dalbergia* when planted along canals successfully checked seepage and helped in mitigating waterlogging. In combination with grasses such as *Leptochloa fusca*, *Brachiaria mutica*, *Phragmites australis*, *Dichanthium annulatum*, and species of *Panicum* and *Paspalum*, these plant species can intercept seepage up to 84% as compared to control.

In northwestern India, trees such as *Terminalia arjuna*, *Acacia nilotica*, *Prosopis juliflora*, and *Eucalyptus tereticornis* and several other tree species raised using saline water for irrigation on calcareous soils enhanced the organic carbon contents of soils by >4.0 g carbon kg^{-1} soil in about 9 years of their growth (Tomar et al. 2003b). Dagar et al. (2016b) reported (based on unpublished data of Dagar et al.) the results of the same experiment after 20 years of growth (Fig. 5.6) and found that *Acacia nilotica*, *Feronia limonia*, *Acacia tortilis*, *Guazuma ulmifolia* (exotic), *Terminalia arjuna*, and *Azadirachta indica* were anong the most efficient species in soil amelioration in these conditions and developed more than 5.5 g kg^{-1} organic carbon in soil.

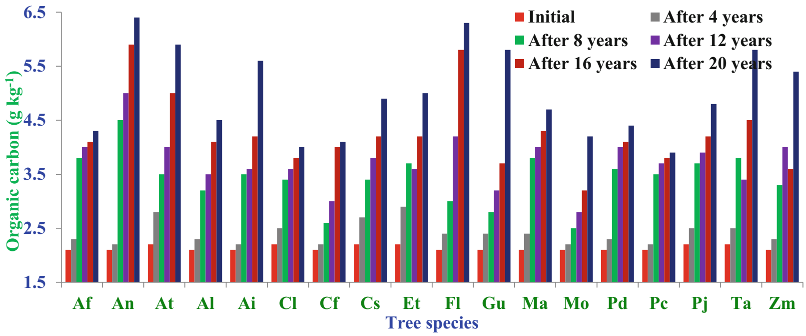


Fig. 5.6 Development of organic carbon by different tree species at different stages of their growth when established with saline groundwater. Depictions: Af, *Acacia farnesiana*; An, *Acacia nilotica*; At, *A. tortilis*; Al, *Albizia lebbeck*; Ai, *Azadirachta indica*; Cl, *Callistemon lanceolatus*; Cf, *C. fistula*; Cs, *Cassia siamea*; Et, *Eucalyptus tereticornis*; Fl, *Feronia limonia*; Gu, *Guazuma ulmifolia*; *Ma*, *Melia azedarach*; *Pd*, *Pithecellobium dulce*; Pc, *Prosopis cineraria*; Pj, *Prosopis juliflora*; Ta, *Tamarix articulata*; Zm, *Ziziphus mauritiana* (Source: Based on Dagar et al., personal communication)

The silvopastoral agroforestry systems on calcareous soils irrigated with saline water were characterized by tree species of *Acacia nilotica* and *Salvadora persica* along with native grasses of *Cenchrus ciliaris* and *Panicum miliare* (Kumari 2008). The litter accumulation on the ground floor in the two systems was *Salvadora persica* system (2.712 ± 0.154 to 3.682 ± 0.136 Mg ha^{-1}) and *Acacia nilotica* system (2.216 to 2.442 ± 0.135 Mg ha^{-1}). The carbon content in ground floor litter ranged from 1.108 to 1.841 Mg C ha^{-1} being greater in the case of *Salvadora persica* silvopastoral system (Kumari et al. 2019). Other important grasses which could be cultivated using saline wáter for irrigation include *Brachiaria mutica*, *Panicum antidotale*, *P. coloratum*, *P. laevifolium*, *P. maximum*, *P. virgatum*, *Cenchrus setigerus*, and *Cynodon dactylon*. For more details, see Dagar (2014).

5.6.2 Nitrogen Reserves and Fluxes

In silvopastoral systems of *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* on a highly sodic soil, nitrogen pool in vegetation was 32.47% and 29.52% of the soil pool, respectively (Kaur et al. 2002a). The litterfall formed a major pathway of the return of nitrogen to the soil that amounted to 0.0 75 to 0.14 Mg N ha^{-1} yr.$^{-1}$. The turnover of fine root biomass in these systems also returned 0.019 to 0.037 Mg N ha^{-1} yr.$^{-1}$ to the soil. The return of total nitrogen from litterfall and fine roots to soil amounted to 0.11 to 0.177 MgN ha^{-1} yr.$^{-1}$. Total nitrogen uptake by the trees and grasses was 0.156 to 0.277 Mg N ha^{-1} yr.$^{-1}$. Thus, nitrogen sequestration in the system was 28.84 to 36.10% of total uptake of the nitrogen in the agroforestry systems (Kaur et al.

2002a). It is reported that *P. juliflora* can also fix atmospheric nitrogen through symbiosis due to the occurrence of the cowpea-type *Rhizobium*.

In the lower Amu Darya River region of Uzbekistan, the conversion of degraded cropland to tree plantations improved soil total nitrogen stocks by 6–30% in 5 years in the upper 20 cm soil layer. The plant-available soil nitrogen was significantly greater in *Elaeagnus angustifolia* plantation as compared to that in *Populus euphratica* and *Ulmus pumila* tree plantations. An increase in the content of available nitrogen in soil was most significant under Russian olive (*E. angustifolia*) being a nitrogen-fixing plant. Despite the presence of excessive salt concentrations within the root zone, the efficiency of biological fixation of nitrogen increased from 40% to almost 100% over the period of 5 years since the trees were planted. A nitrogen fixation rate of 20 kg ha^{-1} was recorded in the first year, increased up to 0.5 t/ha 2 years later, and then stabilized at 0.3 Mg ha^{-1} per year. When the plantation was 4 years old, about 100 kg of nitrogen was released as a result of decomposition of nitrogen-rich leaf litter and incorporated into the soil (Khamzina et al. 2009a, b). Afforestation with mixed-species tree plantations could possibly be a sustainable land-use option for the degraded cropland impacted by salinity (Khamzina et al. 2009b). Increases in the concentrations of plant-available phosphorus by 74% suggest that tree plantations act as an efficient nutrient pump on degraded cropland (Khamzina et al. 2009b). Thus, N_2-fixing trees play a significant role in improving soil fertility.

5.6.3 Soil Bio-Amelioration

Soil microbial biomass is a labile fraction of soil organic matter comprising 1–3% of total soil organic matter (Jenkinson and Ladd 1981) and plays a key role to conserve nutrients for plant growth in seasonally dry tropical forest ecosystems (Singh et al. 1989). In salt-affected soils, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land use type (Kaur et al. 2000) and tree species (Kaur et al. 2002b). The soil microbial biomass at two soil depths in different agroforestry systems was 71.0 to 140.02 kg C ha^{-1} 0 to 7.5 cm and 36.00 to 54.35 kg C ha^{-1} (Fig. 5.7).

There was a significant relationship between microbial biomass carbon and plant biomass carbon ($r = 0.92$) as well as the flux of carbon in net primary productivity ($r^2 = 0.87$, Fig. 5.8). Nitrogen mineralization rates were found greater in silvopastoral systems compared to sole grass system. Soil organic matter was positively correlated with microbial biomass carbon, soil nitrogen, and nitrogen mineralization rates ($r = 0.95$–0.98, $p < 0.01$) (Kaur et al. 2002b).

In energy plantation, soil amelioration occurred due to the growth of *Jatropha curcas* for 6 years on sodic soils. The soil amelioration potential of the energy plantation in terms of increase in soil organic carbon, nitrogen, microbial biomass, and various enzymatic activities was found to be significant when compared to initial soil properties at 0–15 cm soil depth (Singh et al. 2013). There was significant increase in soil organic carbon (SOC), nitrogen (N), phosphorus (P), microbial

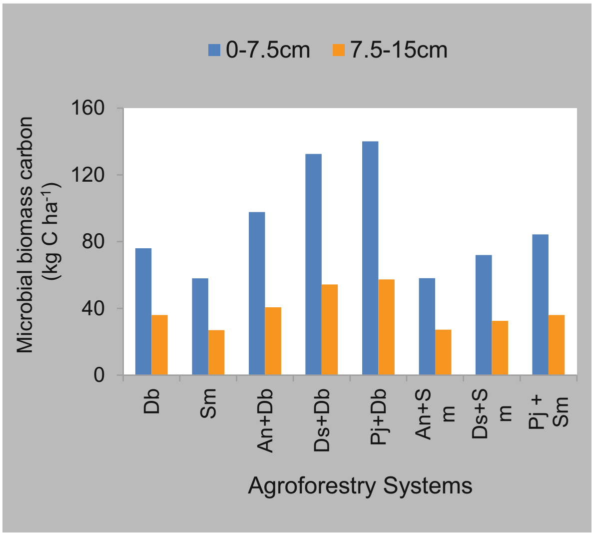


Fig. 5.7 Soil microbial biomass in silvopastoral agroforestry systems. Db = *Desmostachya bipinnata*; Sm = *Sporobolus marginatus*; An + Db = *Acacia nilotica* + *Desmostachya bipinnata*; Ds + Db = *Dalbergia sissoo* + *Desmostachya bipinnata*; Pj + Db = *Prosopis juliflora* + *Desmostachya bipinnata*; An + Sm = *Acacia nilotica* + *Sporobolus marginatus*; Ds + Sm = *Dalbergia sissoo* + *Sporobolus marginatus*; Pj + Sm = *Prosopis juliflora* + *Sporobolus marginatus* (Source: Kaur et al. 2002a, b)

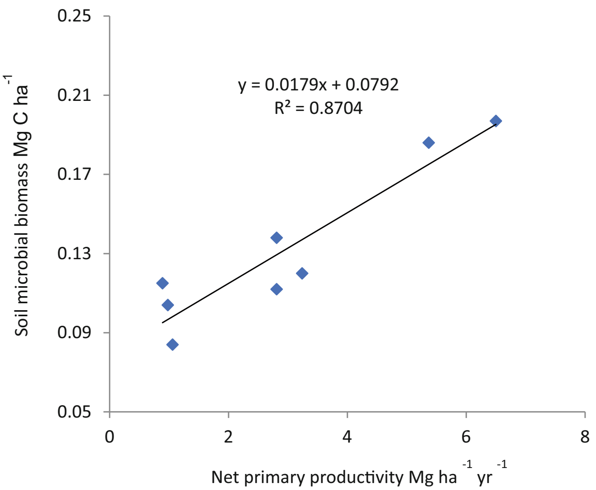


Fig. 5.8 Regression relationship between soil microbial biomass and net primary productivity in a silvopastoral study on a sodic soil at Bichhian, northwestern India (based on Kaur et al. 2002b)

biomass (MB-C, MB-N, and MB-P), and enzyme activities (dehydrogenase, β-glucosidase, and protease) beneath the canopy of *Jatropha curcas* than outside the canopy (Singh et al. 2013).

5.6.4 The Role of Arbuscular Mycorrhizal Fungi Under Salt Stress

AM fungi regulate some of the key processes driving the carbon cycle and also mediate soil C storage. *Desmostachya bipinnata* and *Sporobolus marginatus* are salt-adapted grasses, which showed moderately high diversity of arbuscular mycorrhizal (AM) fungi in their rhizosphere growing on sodic soils (Jangra et al. 2011). The arbuscular mycorrhizal species belonging to *Glomus* and *Acaulospora* have been found to dominate the AM fungal species occurring in the rhizosphere of these salt-adapted grasses. The density of arbuscular mycorrhizal (AM) fungal spores in soil of the sodic grassland systems was 0–15 cm soil depth, 22.8 to 60.8 g^{-1} soil, and 15–30 cm soil depth, 9.6 to 18.4 g^{-1} soil. Arbuscular mycorrhizal root colonization of *Sporobolus marginatus* and *Desmostachya bipinnata* growing on highly sodic soil (Jangra 2010) and *Panicum miliare* growing on saline water irrigated soils (Kumari 2008) showed Y and H type of AM fungal infection in cortical cells and presence of round and globose vesicles with attached hyphae (Fig. 5.9). The *Glomus* spp. and *Acaulospora* spp. were the predominant AM fungal species in agroforestry systems. The AM fungi associated with salt-adapted grasses could play an important role in bio-amelioration and soil carbon storage. Mycorrhizal fungi are reported to sequester large amounts of C in living, dead, and residual hyphal biomass in the soil and may be mediating soil carbon sequestration (Treseder and Allen 2000).

In *Acacia nilotica* and *Salvadora persica* silvopastoral system on saline-sodic soils, the AM root colonization in various grass species was observed to vary from 47.8% to 71.2% (Kumari et al. 2018) (Fig. 5.10). In the agrohorticultural system of

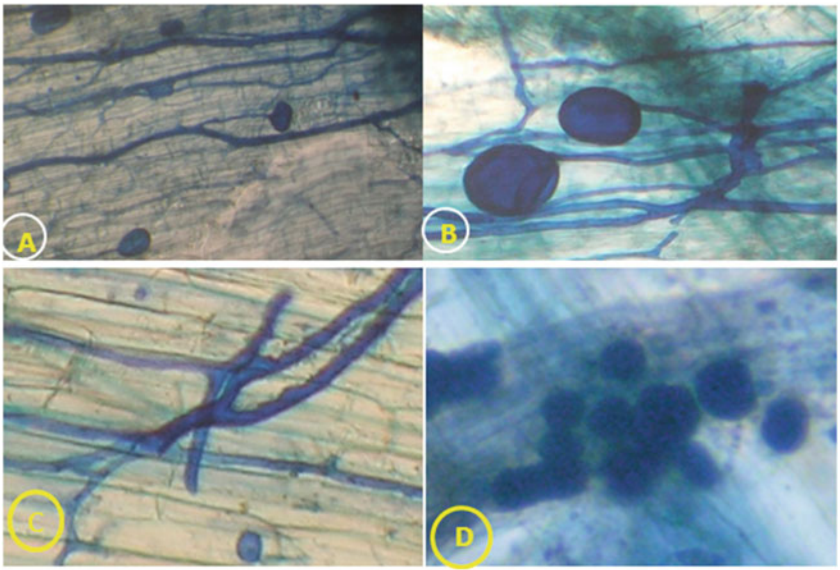


Fig. 5.9 Arbuscular mycorrhizal infection in roots of *Sporobolus marginatus* (**a**–**b**), *Desmostachya bipinnata* (**c**), and *Panicum miliare* (**d**) growing on salt-affected soils

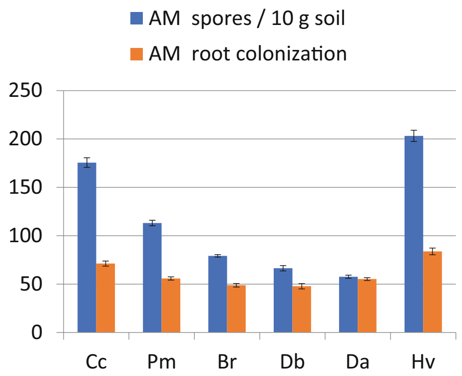


Fig. 5.10 Arbuscular mycorrhiza (AM) spore density and AM root colonization (%) in the rhizosphere soil of predominant grasses in silvopastoral, agrohorticultural systems and the natural grassland on calcareous soil at Hisar, northwestern India (Cc, *Cenchrus ciliaris*; Pm, *Panicum miliare*; Br, *Brachiaria reptans*; Db, *Desmostachya bipinnata*; Da, *Dichanthium annulatum*; Hv, *Hordeum vulgare*) (based on Kumari et al. 2018)

Carissa carandas along with *Hordeum vulgare*, some 23 species of mycorrhizal fungi belonging to *Glomus*, *Acaulospora*, and *Gigaspora* were recorded. The AM fungal species belonging to *Glomus* were more prevalent. The commonly occurring AM fungal species were *Glomus macrocarpum*, *Glomus caledonium*, *Glomus constrictum*, *Glomus pallidum*, *Glomus mosseae*, *Glomus intraradices*, and *Glomus reticulatum* and six unidentified species. In the silvopastoral system and the agrohorticultural system, the spore density in the rhizosphere of predominant grasses varied from 57.6 to 203.2 spores per 10 g^{-1} soil, the value being greatest in the case of *Hordeum vulgare* (Kumari et al. 2018) (Fig. 5.10).

In the agrohorticultural system, the AM fungal root colonization of *Hordeum vulgare* was 83.8%. In the case of *Hordeum vulgare* and various grasses, mycorrhizal root colonization showed H and Y type of infection and the presence of arbuscules and the vesicles in cortical cells.

The AM fungal root colonization was greatest in the case of *Hordeum vulgare* which has been integrated with *Carissa carandas* agrihorticulture system. The AM fungal colonization of roots in various grass species under silvopastoral system ranged from 47.8% to 71.2%. AM fungi exist in two different phases: inside the root and in the soil. The intra-radical mycelium consists of hyphae and other fungal structures such as arbuscules and vesicles. This phase is connected to the soil mycelium. The extracellular mycelium forms spores, exploring a new area for colonization in the soil (Rilling 2004).

5.6.5 Soil Aggregate Composition and Carbon Storage

Soil structure regulates to a large extent many physical, chemical, and biological properties of soil. An aggregate is a naturally occurring group of soil particles, which helps in the movement of air and water through the soil and the protection of soil organic matter (Oades 1984). There are three size classes of soil aggregates, i.e., primary particles (sand, silt, and clay), microaggregates (53–250 μm), and macroaggregates (> 250 μm) (Tisdall and Oades 1982). Soil aggregate stability and soil organic matter are key indicators for soil quality and environmental sustainability in agricultural systems. The soil organic matter (SOM) contained inside these microaggregates is not easily accessed by microorganisms, and the mean residence time of SOM associated with microaggregates and the silt plus clay fraction is higher than that in macroaggregates (Six et al. 2002a, b). Therefore, the incorporation of soil organic carbon into microaggregates and the silt plus clay fraction is a mechanism for carbon sequestration (Skjemstad et al. 1990). Carbon associated with microaggregates within macroaggregates has been highlighted as an early indicator of soil organic carbon changes associated with management practices (Six and Paustian 2014). Ahamad et al. (2012) observed the distribution of water-stable aggregates, and their indices were compared in waterlogged sodic soil with non-waterlogged soil profiles. Average maximum total water-stable aggregates (45.16%) were recorded in 0–15 csm soil depth which decreased with increased soil depth. In 0–15 cm soil depth, macroaggregates increased from 9.9% in soil with pH 8.5 to 20.3% in soil with pH 9.5 in waterlogged condition, and macroaggregates decreased to 2.84% on the same soil in non-waterlogged condition. However, in soil with pH 8.5 in waterlogged condition, macroaggregates increased to 9.9 and 11.4% in 0–15 cm and 15–30 cm soil depths, respectively. In soil with pH 9.5, however, in waterlogged condition, macroaggregates decreased with increasing soil depth. Ahamad and Dagar (2015) also observed that the total water-stable aggregates and soil organic carbon under 7-year-old *Eucalyptus tereticornis* plantation increased through adding of litter and its decomposition. Improvement in soil aggregation was found to be the indicator of improving soil health and sequestering carbon in sodic-saline waterlogged soil in terms of reducing soil pH and electrical conductivity and increase in organic carbon more so in upper 30 cm layer. *Eucalyptus* can successfully be grown by ridge planting as well as block plantation on waterlogged soil. Tree plantation is thus the most viable option to tackle land degradation and to bring the eco-restoration and sustenance of soil resources. *Eucalyptus* helped in binding the soil aggregates, and this was more prominent in block plantation.

On a highly calcareous sandy loam soil irrigated with saline water at Hisar in northwest India, the aggregate composition of soil in the silvopastoral systems of *Acacia nilotica* and *Salvadora persica* showed that the macroaggregates in size classes of 2 mm to 250 μm were low forming about 2 to 18% of the total soil aggregates (Fig. 5.11). In *Acacia nilotica* silvopastoral system, macroaggregates were lower as compared to *Salvadora persica* system. With the increase in soil depth, there was decrease in the percentage of macroaggregates in the soil. The decrease in macroaggregates with increase in soil depth was also observed in *Acacia nilotica* silvopastoral system.

In the natural grassland system, the macroaggregate ranged from 1.01 to 1.97%; the values were lower as compared to silvopastoral system. The proportion of two macroaggregates classes >2 mm and 2 mm–250 μm was greatest in the surface layer

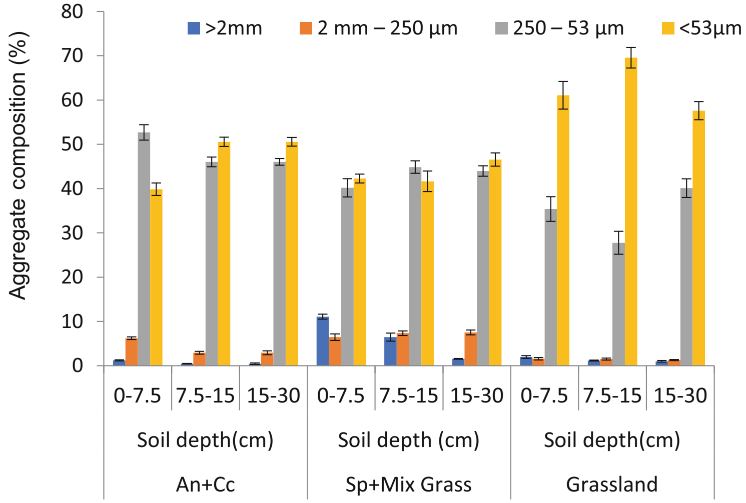
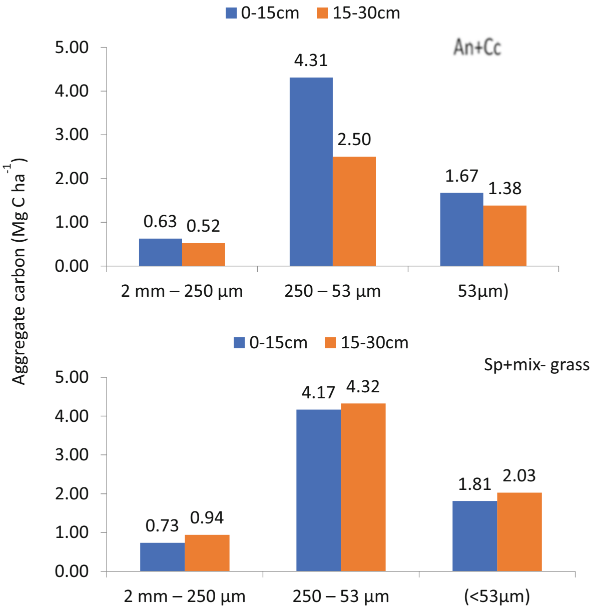


Fig. 5.11 Composition of soil aggregates at 0 to 7.5 cm, 7.5 to 15 cm, and 15 to 30 cm soil depths in silvopastoral systems of *Acacia nilotica* + *Cenchrus ciliaris* (An + CC); *Salvadora persica* + mixed grasses (Sp + mixed grass) and the grassland system on calcareous soils at Hisar

of the *Carissa carandas* + *Hordeum vulgare* system. In *Acacia nilotica* and *Salvadora persica* silvopastoral system, the macroaggregate formation improved under the silvopastoral systems. The silvopastoral agroforestry systems of *Acacia nilotica* and *Salvadora persica* along with native grasses of *Cenchrus ciliaris* and *Panicum miliare* and agrihorticulture system of *Carissa carandas* with *Hordeum vulgare* showed that the agroforestry systems effectively improved the soil structure and strengthened the stability of water-stable soil aggregates (Kumari et al. 2018). This study showed that different agroforestry systems improved the soil organic carbon content and storage in aggregates of different sizes as compared to that of native grassland site (Fig. 5.12). The long-term adoption of agroforestry interventions significantly increased the content of water-stable macroaggregates; the microaggregates ranging from 0.250 to 0.053 mm were the main sites of soil organic carbon storage. The tree-based systems had a greater effect on macro- and microaggregates in surface layer as compared to other depths, suggesting an aggregate stratification phenomenon (Kumari et al. 2018).

There was a significant positive relationship between the OC in bulk soil and those in the microaggregate fractions in three types of agroforestry systems (Fig. 5.12). A significant positive relationship was also observed between the organic carbon concentration in bulk soil and that in the silt + clay fraction on the pooled data across sites ($p < 0.5$) (Fig. 5.13). Further, the results suggested that OC accumulated mainly in the microaggregate fractions and silt + clay associated fractions in the natural grassland system.

Fig. 5.12 Soil aggregate carbon stock at 0 to 15 cm and 15 to 30 cm soil depths in *Salvadora persica* + mixed grasses (Sp + mixed grass) and *Acacia nilotica* + *Cenchrus ciliaris* (An + Cc) silvopastoral systems on calcareous soils at Hisar, northwestern India



5.7 Carbon Sequestration in the Soil–Plant System

Carbon sequestration can occur in plant biomass, organic and inorganic carbon in surface soil, and carbon storage in soil profiles. In terrestrial ecosystems (i.e., soils, trees, and other vegetation), carbon sequestration is a natural process based on photosynthesis and humification of biomass (Lal 2009). Every year, ~121 Pg (Pg = petagram = 10^{15} g) of CO_2-C from the atmospheric pool is photosynthesized into plant biomass, out of which ~60 PgC is returned back to the atmosphere by plant respiration and the remaining 61.6 PgC by soil respiration. Plant biomass and soil organic matter constitute the major pool of carbon in terrestrial ecosystems. The biotic pool in vegetation stores about 610 PgC at any given time (Amundson 2001). Maintaining the stores and sink of carbon in agroforestry could play a key role in climate change mitigation as well as help in adapting to changing environmental conditions.

5.7.1 Carbon Sequestration in Plant Biomass

The trees on salt-affected soils have the potential for carbon sequestration by increasing soil carbon and plant biomass production (Bhojvaid and Timmer 1998; Garg 1998; Kaur et al. 2002a, b). In an age sequence of *Prosopis* plantations, trees have been found to ameliorate highly sodic conditions by alleviating sodium toxicity and improving the buildup of soil fertility (Bhojvaid and Timmer 1998). These

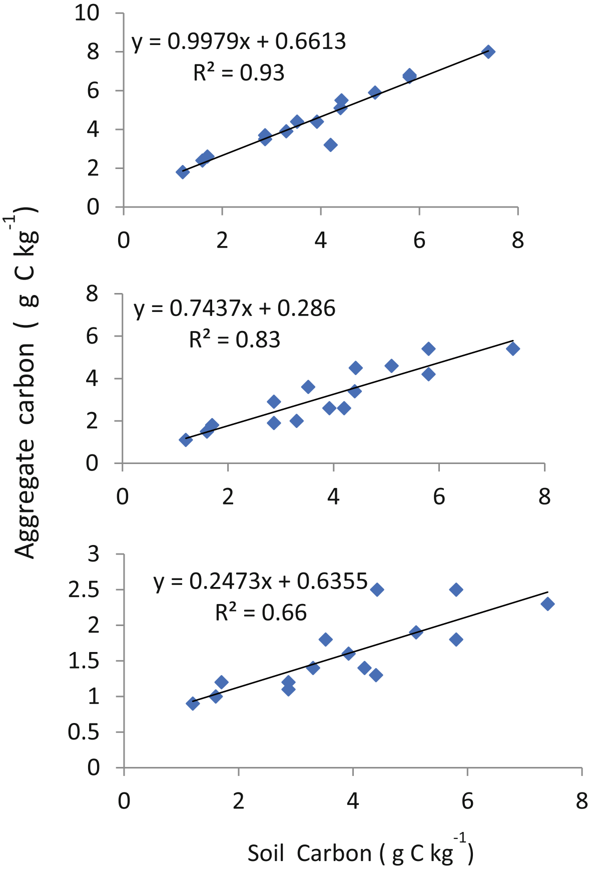


Fig. 5.13 Relationship between soil carbon (g C kg^{-1} soil) and the aggregate carbon (g C kg^{-1} soil aggregate) in different soil fractions: (**a**) (2 mm–250 μm), (**b**) (250–53 μm), (**c**) (<53 μm)

workers showed the annual rate of increase of 1.4 Mg C ha^{-1} yr.$^{-1}$ over a 30-year period of plantation. Glenn et al. (1992) estimated that 0.6–1.2 gigatonnes 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.

Carbon pools in *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* silvopastoral systems on a sodic soil at Bichhian are shown in Fig. 5.14. In silvopastoral agroforestry systems on sodic soils at Bichhian, 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. 2002a). 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. 2002a). 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}.

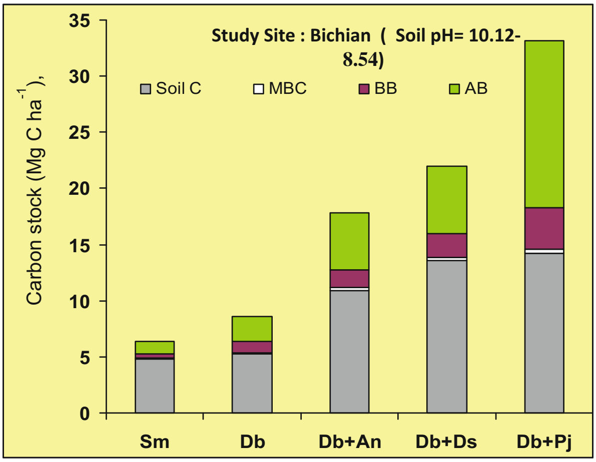


Fig. 5.14 Carbon sequestration in grassland and grass + tree systems (silvopastoral systems) on a sodic soil at Bichhian, northwestern India. Sm, *Sporobolus marginatus*; Db, *Desmostachya bipinnata*; Ds + Db, *Dalbergia sissoo* + *Desmostachya bipinnata*; *Db* + An, *Desmostachya bipinnata* + *Acacia nilotica*; Db + Pj, *Desmostachya bipinnata* + *Prosopis juliflora* (based on Kaur et al. 2002a)

In southwestern Australia, the rates of C sequestration in biomass of *E. 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). The underutilized species like *Elaeagnus angustifolia*, *Ulmus pumila*, and *P. euphratica* showed high potential for afforestation of the degraded cropland in the lower Amu Darya River region of Uzbekistan. After 5 years of afforestation in Khorezm, the soil organic C (SOC) stocks rose by 10–35%, adding 2–7 Mg C ha^{-1} to the upper 0–20 cm soil layer, with *E. angustifolia* being the most effective tree species in soil C sequestration (Khamzina et al. 2012). Depending on tree species, C sequestration in woody biomass ranged from 11 to 23 Mg ha^{-1} (Khamzina et al. 2012).

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 one grass) on moderately alkaline soils (pH 8.36 to 8.41) at Kachchh, Gujarat, northwestern India (Mangalassery et al. 2014). This study showed that maximum carbon was sequestered by silvopastoral 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 silvopastoral system of *Azadirachta indica* + *C. ciliaris* and *Azadirachta 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% to 60.0% more total soil organic carbon stock compared to the tree system and 27.1–70.8% more in comparison to the grass-only system. Thus, silvopastoral system sequestered more carbon (Mangalassery et al. 2014).

Biomass and carbon sequestered by 5-year-old and 4-month-old clonal *E. tereticornis* on water-logged soils at Puthi, Hisar, northwest India, was 15.5 Mg ha^{-1} (Jeet-Ram et al. 2011). The *Eucalyptus*-based agroforestry on water-logged soils showed soil carbon storage of 15.823 Mg C ha^{-1}. Compared to baseline of the cropland, the net carbon sequestration amounted to 4.452 Mg C ha^{-1} over a

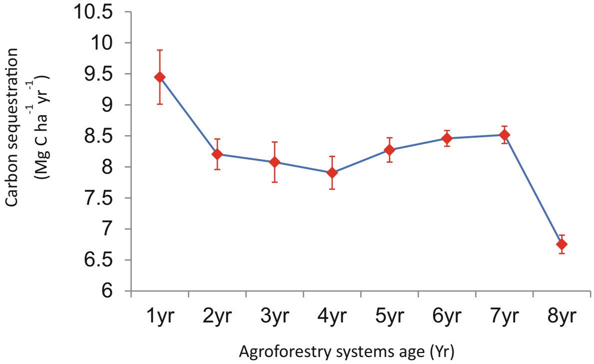


Fig. 5.15 Carbon sequestration rates in Mg C ha^{-1} $yr.^{-1}$ in tree biomass of *Eucalyptus tereticornis* agroforestry systems on moderately alkali soil at Salimpur, Kurukshetra, India (From Gaur 2013)

period of 4 years. Carbon storage in plant biomass (Mg C ha^{-1}) and carbon flux in net primary productivity (Mg C ha^{-1} $yr.^{-1}$) of clonal *Eucalyptus tereticornis* agroforestry in shallow water-table areas in Puthi, northwest India, showed that total carbon storage in plant ranged from 9.5 (in 1 m × 3 m space) to 22.8 Mg C ha^{-1} (in 1 m × 1 m space) after 6 years of growth and 90.6 Mg ha^{-1} in block plantation of the same age. Carbon flux in net primary productivity was 1.6 to 3.8 Mg C ha^{-1} $yr.^{-1}$ in different spaces and 15.1 Mg C ha^{-1} $year^{-1}$ in block plantation (Table 5.7; Dagar et al. 2016a).

According to Gaur (2013), the carbon sequestration rate in 01 to 8-year-old *Eucalyptus tereticornis* trees ranged from 9.446 to 6.752 Mg C ha^{-1} $yr.^{-1}$ (Fig. 5.15). The potential of agroforestry systems to sequester carbon depends on the type of system, plant species composition, plantation age, environment factors, and management practices (Jose 2009).

Neumann et al. (2011) 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 121 agroforestry sites (comprised of 32 species); the average age of the plantings was 16.5 years. The various factors influencing potential productivity of the agroforestry systems included species choices, planting designs, land management practices, and climatic conditions. The average aboveground carbon sequestration rate for all measured plantations was found to be 9.49 Mg of carbon dioxide equivalents per hectare per year (CO2-e Mg ha^{-1} $yr.^{-1}$) (Neumann et al. 2011) (Table 5.8). For different systems, the carbon sequestration rates were (CO2-e Mg ha^{-1} $yr.^{-1}$) as follows: tree-form eucalypts, 10.55; mallee-form eucalypts, 6.34; and non-eucalypt trees, 6.92 (Table 5.8). In these lower rainfall areas, tree growth and carbon sequestration rates are naturally low, and mallee eucalypts could be the best option (Neumann et al. 2011)

Biomass production from biosaline agroforestry in waterlogged, saline-sodic soils in India was found to sequester 6 Mg CO_2eq ha^{-1} over the 15-year lifetime of the plantation (Wicke et al. 2013). The emissions from agrochemical and fossil fuel use could be compensated by carbon sequestration in belowground biomass and soil. The economic value of the carbon sequestration is small and ranges between 0.003 and 0.046 kV ha^{-1} depending on the carbon credit price assumed.

Table 5.8 Aboveground dry biomass and carbon sequestration rates from trees and mallees observed in the southern Murray-Darling Basin Region of South Australia (based on Neumann et al. 2011)

	Rainfall (mm)	Dry biomass (Mg ha^{-1} $yr.^{-1}$)	Carbon sequestration (Mg C ha^{-1} $yr.^{-1}$)	Carbon sequestration CO_2e (Mg ha^{-1} $yr.^{-1}$)
Tree eucalypts	435	5.79	2.87	10.55
Mallee eucalypts	351	3.48	1.73	6.34
Tree non-eucalypts	452	3.80	1.89	6.92
Tree form only	437	5.58	2.77	10.15
All plants	422	5.21	2.58	9.49

5.7.2 Soil Carbon Sequestration

The soil organic matter is an important indicator of soil quality and the ecosystem services. Improving SOC pool is an important strategy of reclaiming salt-affected soil. The goal is to create a positive ecosystem C budget. Soil carbon is in a constant state of flux, responding to inputs of organic matter, loss through grazing, decomposition, and mineralization from microbes and other soil fauna which convert organic matter to CO_2. Changes in soil management that increase input rates may drive changes in the carbon pool size. The capacity for soils to sequester carbon is finite, and there are specific maximum equilibrium levels of soil organic matter that can be achieved for any farming system due to the climatic and edaphic limits on plant dry matter production and decomposition rates (Powlson et al. 2011).

Soil carbon sequestration in agroforestry systems on salt-affected soils has been studied by several workers (Table 5.9). Soil carbon sequestration potential in 0–30 cm soil layer ranged from 6.839 to 27.09 in some agroforestry systems and grassland systems of salt-affected soils. In the *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* agri-silvopastoral systems on sodic soils at Bichhian, northwest India, the soil carbon pool was 13.431 Mg C ha^{-1}, *Prosopis juliflora* + *Desmostachya bipinnata*, and 9.621 Mg C ha^{-1}, *Prosopis juliflora* + *Sporobolus marginatus* (Kaur et al. 2002a). The soils at different sites were found to store 25.86 to 99.33 Mg CO_2eq ha^{-1}, which accounted for 25.86 to 99.33 carbon credits/ha for soil carbon sequestration. Assuming $10 price for one carbon credit, the monetary value of carbon storage comes out to be ranging from 259 to 993 US$ ha^{-1}.

Soil carbon stock in 0 to 15 cm and 15 to 30 cm soil depths in grassland and different agroforestry systems of *Carissa carandas* + *Hordeum vulgare*, *Salvadora persica* + mixed grass silvopastoral system, and *Acacia nilotica* + *Cenchrus ciliaris* silvopastoral system are compared in Fig. 5.16. The total organic carbon (0–30 cm soil depth,) was 6.839, 21.195, and 20.181 Mg C ha^{-1} for the native grassland, the

Table 5.9 Soil carbon sequestration at 0–30 cm soil depth in different agroforestry systems on salt-affected soils in India (based on Gupta and Dagar 2016)

Agroforestry system	Site	Soil carbon sequestration (Mg C ha^{-1})	CO_2 sequestration (Mg CO_2 ha^{-1})	Reference
Prosopis juliflora + *Desmostachya bipinnata* silvopastoral system	Sodic soils at Bichhian, Northwest India	13.431	49.247	Kaur et al. (2002b)
Prosopis juliflora + *Sporobolus marginatus* silvopastoral system	-do-	9.621	35.28	Kaur et al. (2002b)
Acacia nilotica + *Cenchrus ciliaris* silvopastoral system	Saline-sodic calcareous soils, Hisar, India	20.50	75.17	Kumari et al. (2018)
Salvadora persica + native grasses silvopastoral system	-do-	19.48	71.43	Kumari et al. (2018)
Carissa carandas + *Hordeum vulgare* agrihorticulture system	-do-	14.13–14.25	51.81–52.25	Kumari et al. (2018)
Grassland	-do-	7.06	25.89	Kumari et al. (2018)
Eucalyptus clonal agroforestry on waterlogged soils	Puthi, Haryana state, India	22.8 (in 1 m × 1 m space) 90.6 in block	83.68 332.5	Dagar et al. (2016a)
Jatropha curcas, energy plantation soil depth = 15 cm	Sodic soil, Banthra, Lucknow, India	10.428–7.650	38.237–28.050	Singh et al. (2013)

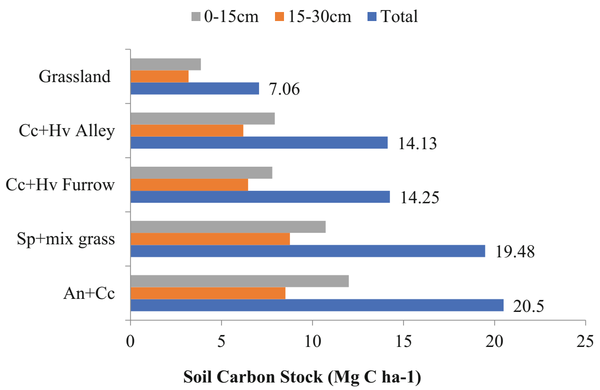


Fig. 5.16 Soil carbon stock in 0 to 15 cm and 15 to 30 cm soil depths in grassland and different agroforestry systems. Cc + Hv alley, *Carissa carandas* + *Hordeum vulgare*; *Sp + mixed grass*, *Salvadora persica* + mixed grass silvopastoral system; An + Cc, *Acacia nilotica* + *Cenchrus ciliaris* silvopastoral system (based on Kumari et al. 2018)

Acacia nilotica + *Cenchrus ciliaris* silvopastoral systems, and *Salvadora persica* system, respectively. The soil organic carbon was greater (20.181 to 21.195 Mg C ha^{-1}) in the case of silvopastoral systems as compared to the native grassland (6.839 Mg C ha^{-1}). Thus, integration of trees with forage grasses improved soil organic carbon significantly on calcareous soils irrigated with saline water (Kumari et al. 2018).

Across the Australian wheat belt, it has been estimated that over 60% of soil organic carbon has been lost from the top 10 cm of soil, suggesting that there may be opportunity for extra soil carbon sequestration (Chan et al. 2010). In the western Australian wheat belt, the restoration of native eucalypt forests for managing degraded agricultural landscapes is a critical part of managing dryland salinity and rebuilding biodiversity. Harper et al. (2012) conducted two 26-year-old reforestation experiments with four *Eucalyptus* species (*E. cladocalyx* var. *nana*, *E. occidentalis*, *E. sargentii*, and *E. wandoo*) compared with agricultural field. SOC stores (to 0.3 m depth) ranged between 33 and 55 Mg ha^{-1}, with no statistically significant differences between tree species and adjacent farmland (Harper et al. 2012). In contrast, the reforested plots contained additional carbon in the tree biomass (23–-60 Mg ha^{-1}) and litter (19–34 Mg ha^{-1}), with the greatest litter accumulation associated with *E. sargentii*. Litter represented between 29 and 56% of the biomass carbon, and the protection or utilization of this litter in fire-prone, semiarid farmland will be an important component of carbon management (Harper et al. 2012). These workers emphasized the importance of considering litter in reforestation carbon accounts.

5.7.3 Climate Change Mitigation and Adaptation

In recent times, atmospheric concentration of carbon dioxide has increased from preindustrial levels of 280 ppm to about 406.67 ppm on August 25, 2018, indicating a pronounced human impact on terrestrial and marine ecosystems (IPCC 2014). Averaged over all land and ocean surfaces, temperatures have warmed 0.85 °C (0.65 to 1.06 °C) over the period 1880 to 2012 (IPCC 2014). The preindustrial level of carbon dioxide was 280 ppm, whereas the safe limit of CO_2 levels in the atmosphere is 350 ppm.

Agroforestry can add a high level of diversity on degraded lands with an accompanied increased capacity for supporting numerous ecological and production services that impart resiliency to climate change impacts (Verchot et al. 2007; Schoeneberger et al. 2012; Gupta and Dagar 2016; Dagar et al. 2016b). The mixing of woody plants into crop, forage, and livestock systems provides greater resilience to the interannual variability through crop diversification as well as through increased resource-use efficiency (Olson et al. 2000). Climate change adaptation refers to the use of a global change scenario to estimate the impact of global change on the system of interest and then undertake such strategies that adapt the system to these. Ecosystems through more structural diversity, functional diversity, and diversified production can contribute to adaptation because of multiple links between ecosystem services and climate change (Locatelli 2016).

The potential for agroforestry for carbon sequestration and dryland salinity reduction has been analyzed for low rainfall (330 mm year^{-1}) and medium rainfall (550 mm year^{-1}) salinity-impacted regions in western Australia for the purpose of selling carbon credits, from a landholder's perspective (Flugge and Abadi 2006). The analysis used a whole-farm optimization model to determine the viability of carbon sequestration activities. Trees used for carbon sequestration in both models were assumed to be *Eucalyptus* species that are suited to medium to low rainfall regions in western Australia. This study indicated that the price of carbon needed to be higher (A$25–A$46/tCO2-e) than expected (A$15/tCO2-e) so as to make growing trees an attractive investment for landholders in regions under high and low rainfall areas. The carbon sequestration activities can only be adopted by land owners if the carbon price and salinity prevention benefits are taken into consideration (Flugge and Abadi 2006). Western Australian research has also shown that competition for water and nutrients between mallee trees and crops is a significant cost to farmers and needs to be considered while designing integrated mallee agroforestry systems (Sudmeyer et al. 2012). The emerging carbon market may provide a new agroforestry option for landholders through carbon sequestration.

There is large variation in carbon sequestration rates for salt-affected soils (Gupta et al. 2016), which can be attributed to differences in the soil type, initial soil conditions, climate, and differing litter production rates of the tree species (Wicke et al. 2013). Biosaline (agro)forestry systems may potentially have the positive effect of improving water infiltration and soil moisture retention. It is interesting to note that including trees in the agricultural production system can help remove excess water, thereby reducing waterlogging. Various studies have shown that if properly implemented, the biodrainage systems can lower groundwater tables (see Wicke et al. 2013; Dagar et al. 2016a). Dagar et al. (2016b) and Jat et al. (2016) have dealt in detail how agroforestry systems can be adapted and help in mitigating climate change. These not only sustain livelihood security but also improve the environment including biodiversity.

5.8 Conclusions

The service function of the agroforestry systems such as biodiversity, carbon sequestration, pollination, water quality, salinity control, biomass production, and soil conservation is gaining the attention of researchers, planners, and politicians. Thus, productivity-integrated tools along with ecosystem functioning and services are needed to ensure sustainable agroforestry in saline environments. Improving soil productivity of salt-affected soils is critical to formulate management strategies so as to meet increasing demands of food, fodder, biomass energy, and industrial products for human society. Agroforestry systems can reduce risks under climate change by creating more diversified systems with diversified products. The complexity and diversity of agroforestry systems have the potential for meeting greenhouse gas objectives as well as providing the resilience for attaining the ecosystem service goals on a long-term basis

There is a need to implement a landscape approach for restoration based on continual learning and adaptive management, participatory and user-friendly monitoring, and strengthening stakeholder capacity. More rigorous discussion is needed on linkages between soils and ecosystem services. Models need to be developed with the goal of understanding and predicting key dynamics of soil carbon in relation to ecosystem processes and socioeconomic drivers under scenarios of global and regional change. There is a need to develop climate-smart ecological restoration that insures against future risks of climate change and other rapid global changes.

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6 Silvopasture Options for Enhanced Biological Productivity of Degraded Pasture/Grazing Lands: An Overview

Jagdish Chander Dagar and Sharda Rani Gupta

Abstract

Grazing lands in different regions of the world have become very fragile and unsustainable due to unbalanced utilization, resulting in large-scale degradation. The primary cause of degradation is the demographic pressure on land, leading to loss of vegetative cover through deforestation and overgrazing. About 60% of the world's agricultural land is grazing land, supporting about 360 million cattle and over 600 million sheep and goats. Many of the world's grazing areas are threatened with degradation, especially in the semi-arid and subhumid zones. For an estimated 100 million people in arid areas, and probably a similar number in other zones, grazing livestock is the only possible source of livelihood; therefore, the management of grazing lands needs priority not only for livelihood security of millions of poor people but also for the environmental security. There are sufficient evidences which prove that even simple protection from grazing or by control grazing can result in a significant increase in production, greater tree regeneration, erosion control and amelioration of soil in terms of increase in organic carbon, nutrients and biological activity. The various approaches for managing the grazing lands include control grazing or complete fencing, judicious application of fertilizers, introduction of legume components, optimizing harvest schedules, moisture conservation, fodder farming under old plantations, use of improved productive varieties of grasses and legumes for fodder production and retaining or introducing nitrogen-fixing trees. Protection of existing trees on grazing lands and introduction of nitrogen-fixing trees

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constitute a sustainable and productive silvopastoral system. Multipurpose tree species can also be adopted in degraded grazing lands with poor vegetation cover or by developing location-specific silvopastoral models. This chapter describes the status of grazing lands and approaches to improve their productivity and develop sustainable silvopastoral agroforestry systems.

Keywords

Silvopastoral systems · Productivity · Carrying capacity · Degraded lands · Overgrazing · Productivity · Grassland management

6.1 Introduction

Grassland is a biome which is dominated by grasses and other herbaceous flowering plants and a variety of scattered trees and bushes. Climatically climax grasslands are those that result from prevailing climatic conditions, whereas the managed grasslands represent intermediate successional stages. In climatically climax grasslands, seasonal water deficits and periodic droughts prevent the establishment of forests in those regions. Grasslands in the wider sense are among the largest ecosystems in the world; their area is estimated to be 40% of the land area including savannahs with scattered trees and open-canopy grassy woodlands (WRI 2001; White et al. 2000; Gibson 2009; Dixon et al. 2014). Tropical grasslands cover much of Africa as well as large areas in Australia, South America and India. African savannahs represent one of world's largest expanses of tropical grasslands, and these are maintained by wild herbivores as well as by nomadic pastoralists and their cattle, sheep and goats. Grasslands are important ecosystems because they are frequently used for livestock grazing, provide important ecosystem services and also serve as carbon sinks. It is estimated that ~ one billion people worldwide depend directly on grasslands for their livelihoods (Suttie et al. 2005). Grasslands are among the most critically endangered biomes due to widespread conversion for multiple anthropogenic uses, including 70% of global agriculture (Hoesktra et al. 2005), besides increased pressures from human and livestock populations (Suttie et al. 2005).

The term 'grazing land' adopted in 1972 at Montpellier (France) by UNESCO Expert Panel on Man and Biosphere Programme denotes a piece of vegetation wherein grazing occurs. Pandeya (1988) referred the closely related terms in this context, viz. *grassland*, a land with more than 80% occupied by grasses; *rangeland*, a piece of vegetation wherein grazing occurs or can occur; and *pasture*, a piece of land in which grasses are grown for livestock feeding. World Resource Institute's land classification (WRI 2000) considers these permanent pastures as grasslands. Grasslands provide essential ecosystem services and support livelihoods in a number of ways including genetic resource for food production, resource for energy production and raw material in industrial production and for carbon sequestration, hence climate change mitigation (FAO 2011). Misra (1987) considered pastures as grazing lands in the Indian context since they are maintained under the anthropogenic pressure and grazing. Managed grazing lands, designed for the production of animals for consumption, cover about 25% of the global land surface and have larger geographic extent than any other forms of land use (Asner et al. 2004).

About 60% of the world's agricultural land is grazing land, supporting about 360 million cattle and over 600 million sheep and goats, and these supply about 10% of the world's production of beef and about 30% of the world's production of sheep and goat meat (*www.fao.org/3/x5304e03.htm*). Further, in an estimated 100 million people in arid areas, and probably a similar number in other zones, grazing livestock is the only possible source of livelihood (*www.fao.org/3/x5304e03.htm*). Arid rangelands are a dynamic and highly resilient ecosystem provided that the number of people and animals which the land supports remains in balance with their environment. Indeed, the ability to recover after drought is one of the main indicators of long-term environmental and social sustainability of arid grazing systems. Many of the world's grazing areas are threatened with degradation, especially in the semi-arid and subhumid zones. As a result of population pressure, and policies which favour cropping, much of the best pasture is being converted to agriculture. When, after a few years, the land is exhausted and returned to fallow, it cannot be converted to good pasture. Therefore, it is important to restore these valuable resources to sustain the livelihood security of a population of millions.

There is dependency of people on the rangeland for ecosystem services, and for their livelihoods, degradation of this resource can have profound ecological and societal effects. By their nature, rangelands are fragile ecosystems and when mismanaged readily result in degradation, loss of biodiversity and water retention capacity, carbon emissions and reduced productivity. Protection from grazing by fencing, introduction of productive forages and nitrogen-fixing trees, the use of organic and bio-fertilizers and adoptable policy issues may help in developing viable agroforestry systems, which in turn will help in restoring these degraded resources and increase productivity and sustain livelihood. This chapter discusses the status of grazing lands and their production potential, goods and services, the main causes of rangeland degradation and approaches for their management. The silvopasture systems for degraded pasture/grazing lands in different regions of the world have been described.

6.2 Status of Grazing Lands

6.2.1 Origin, Evolution, Extent and Distribution of Grassland Systems

As discussed by Gibson (2009), grasses arose in the late Cretaceous-early Tertiary, but they diversified and spread into large vegetation formations in the mid-late Miocene (12–5.3 million years ago (Ma)). The date of earliest appearance of grasslands varies from region to region. For example, in North America, it was towards the end of the Miocene (8–5 Ma) (Axelrod 1985), although savannah or short-sod grasslands appear to have originated in the early Miocene (c.19.2 Ma) (Stromberg 2004). In South America, grass-dominated ecosystems possibly could have arisen as early as the Eocene-Oligocene boundary (34 Ma) (Jacobs et al. 1999). In Central and Western Europe, the grasslands of the present times are secondarily anthropogenic and arose from farming and pastoralism following the spread of Neolithic husbandry in the Holocene (Bredenkamp et al. 2002). The modern North American tall grass, prairie is also considered of recent origin, following the retreat of woodland during the warm, dry hypsithermal period c.4000 years ago. In several regions, a succession of vegetation types can be recognized in the Cenozoic fossil record, as climate dried out progressively. For example, in Central Australia during the past 50 million years, tropical rainforest gave way successively to savannah, grassland and, finally, desert. The rapid and global spread of C_4-dominated grassland in the late Miocene (5–8 Ma) reflects changes in the climate conducive to frequent fire (Keeley and Rundel 2005) including increased seasonality of rainfall (Osborne 2008). A characteristic type of grassland in cool, moist parts of the Southern Hemisphere is tussock grasslands that occur at various latitudes. According to Jacobs et al. (1999) and Gibson (2009), the major phases in the evolution of grasses and grasslands can be summarized as (i) Cretaceous as origin of Poaceae in forest margins or shade, (ii) opening of forested environments in early to middle Tertiary, (iii) increase in abundance of C_3 grasses in middle Tertiary, (iv) origin of C_4 grasses in middle Miocene possibly and (iv) spread of C_4 grass-dominated ecosystems at the expense of C_3 grassland and/or woodland in the late Miocene.

Van Dyne et al. (1978) opined that the establishment of grasslands and grazing animals as major life forms extends well back into geological history where fossil records of grasses have been known from the Tertiary, and true grasses have been well developed at least as long as 6 to 12 million years ago. The fossil record of grasses is scanty, but it is assumed that they emerged as a distinct class of angiosperm complex during late Cretaceous times or even earlier when flowering plants were spreading throughout the world. The Earth has seen a long history of development of grasslands which were able to withstand harsh climates and the grazing and trampling by such animals as bison, elk and deer in North America; a variety of antelope, zebra, wildebeests and other animals in Africa; and marsupials in Australia. The grazing animals and the plant upon which they grazed have evolved simultaneously and thus are adapted to each other.

Rangelands are important for the maintenance of ecosystem functions and biodiversity. In addition to providing feed for livestock, they play an important role as a habitat for wildlife, for water retention and for the conservation of plant genetic resources. The flora of rangelands is rich with about 750 genera and 12,000 grass species. These ecosystems are also important for the maintenance of fauna; for example, grasslands contain 11% of the world's endemic bird areas (White et al. 2000) and contribute to the maintenance of pollinators and other insects that have important regulating functions. Ecosystem benefits, especially regulating services such as water infiltration and purification, climate regulation (e.g. carbon sequestration) and pollination, have begun to be assigned an economic value, and systematic data-gathering in rangelands of both developed and developing countries is a global priority.

Table 6.1 Major pastoral systems and their regional zones (*http://www.fao.org/3/y2647e/y2647e02.htm*) Source: FAO (2001)

Zone	Main animals	Current status
Sub-Saharan Africa	Cattle, camel, sheep, goats	Declining due to advancing agriculture
Mediterranean	Small ruminants	Declining due to enclosure and advancing agriculture
Near East and South-Central Asia	Small ruminants	Declining in some areas due to enclosure and advancing agriculture
India	Cattle, camel, sheep, goats	Declining due to advancing agriculture but peri-urban livestock production expanding
Central Asia	Yak, camel, horse, sheep, goats	Expanding following de-collectivization
Circumpolar	Reindeer	Expanding following de-collectivization in Siberia but under pressure in Scandinavia
North America	Sheep, cattle	Declining with increased enclosure of land and alternative economic opportunities
Andes	Llama, alpaca	Contracting llama production due to expansion of road systems and European model livestock production but expansion of alpaca wool production
South American	Cattle, sheep	Expanding where forests are converted to savannah and lowlands but probably static elsewhere

Table 6.2 Main types of grasslands in the world (from FAO 2000)

Category	Distribution
Tropical grasslands	Africa, South America, northern Australia, India
Prairie/steppe	North America, Central Eurasia, South Africa
Temperate grasslands	Europe, North America, Australia, New Zealand, Asia
Tundra	All subarctic regions

Source: Grassland world statistical data, FAO (2000)—accessed on 15-09-2019 (www.fao.org/uploads/media/grass_stats_1.pdf)

Pastoralism, the use of extensive grazing on rangelands for livestock production, is one of the key production systems in the world's drylands. Pastoral societies have developed strategies that continuously adapt to limited, highly variable and unpredictable resource endowments (e.g. by migratory livestock rearing), but both the rangelands and their users are also vulnerable to the changes brought by demographic pressure, conversion of cropland and climate change. Fluctuations in rainfall and drought are recurring problems in rangelands—for example, 70 million people in the Horn of Africa, many of whom are pastoralists, suffer from long-term chronic food insecurity (FAO 2000). The grazing animals and the plant upon which they grazed have evolved simultaneously and thus are adapted to each other. Major pastoral systems and how they evolve with time are listed in Table 6.1. Further, the extent of important grasslands of the world is listed in Table 6.2.

Considerable academic debate has focused on evolution, development and distribution of the natural grasslands (US/IBP 1973; Walter 1973; Van Dyne et al. 1978; Singh et al. 1979; Coupland 1992; Dagar and Singh 2003; Suttie et al. 2005; Pathak and Dagar 2015). The temperate natural grasslands exist only in Eurasia and North America (prairies and steppes), while most of the temperate grasslands in Europe are recognized largely as artefacts greatly influenced by anthropogenic factors, and those of the Southern Hemisphere are tropical or subtropical. Most of the European and Japanese grasslands represent semi-natural grasslands created and maintained by man and date back to the initiation of forest clearing, which in Europe occurred during Roman settlement in first few centuries AD (Van Dyne et al. 1978). Tropical grasslands exist in India, East and West Africa and Central and South America. Many of the world's original grasslands have been largely converted to croplands or to seeded pastures. Still, these regions carry large number of grazing animals. Many of the world's original forests have been converted to grasslands. Perhaps some 40% of the Earth's land surface is used by grazing animals receiving the bulk of their year-long diet from herbaceous plants, predominantly grasses.

It is considered that the natural grasslands of temperate latitudes exist only in Eurasia and North America. These are the prairies and steppes. Most grasslands of temperate Europe are artefacts, and those of the Southern Hemisphere are tropical or subtropical. Tropical grasslands exist in East and West Africa, Central and South America, some areas of northern Australia and India. The relationship of grasslands to other vegetation types and to climatological conditions has been discussed in detail by Walter (1973) and Singh and Gupta (1992). Van Dyne et al. (1978) reported a grassland map and isoclimatic zones of grasslands of the world. The precipitation-evaporation ratio and precipitation seasonality are important factors in producing different types of grasslands and in differentiating between the habitats of grasslands and forests. Grassland climates have large extremes and occur under a very broad range of mean annual temperature and rainfall. The climates vary from temperate to tropical with annual rainfall ranging from about 250 mm per year in arid grasslands to more than 1000 mm per year in mesic grasslands. The precipitation generally occurs as frequent light rains over an extended period (90 days or more). The tropical and subtropical grasslands, savannahs and shrublands are characterized by rainfall levels ranging from 900 to 1500 mm per year. Grasslands often experience very high intra- and inter-annual variability in rainfall. Many grasslands experience periodic droughts and a dormant season based on seasonal dry or cold conditions. At local scales, soil water availability in grasslands is often highly correlated with plant physiological processes, plant productivity and soil microbial activity.

6.2.2 Main Types of Grasslands

The World Wide Fund (WWF) for Nature has classified the grasslands into four major groups which include tropical and subtropical grasslands, savannahs and shrubland; temperate grasslands, savannahs and shrubland; flooded grasslands and savannah; and montane grasslands and shrubland. The various grassland types are briefly described as follows:

6.2.2.1 Temperate Grasslands

Major grasslands in the temperate regions of the world include the steppes of Central Eurasia, the velds of the high plateaus of Southern Africa, the pampas of Argentina and the prairies of North America. Broadly speaking, they occur in areas where rainfall (25–75 cm per year) is intermediate between those of deserts and forests. Climate is typical continental, with long, cold winters and hot summers. Recent research confirms that, of all the world's 14 biomes, temperate grasslands are at greatest risk, as these systems are highly altered while being the least protected. Temperate grasslands cover about 8% of the Earth's terrestrial surface.

Fire has helped grasses to outcompete woody plants that invade the grassland. Forbs (composites, legumes, etc.) are constantly present but are always less important constituents of prairies (Blair et al. 2014). The tall grass prairies of North America or the velds of South Africa are thought to be as disturbance-dependent communities (Blair et al. 2014). Smaller areas occur in Southeastern Australia and the drier parts of New Zealand. In these grasslands, periodic fires, droughts and the activities of grazers are essential to prevent grassland transforming to other ecosystem types. Steppes characterize large part of the semi-arid to subhumid lands of the temperate zone in Great Plains of North America and the steppes of Eurasia. The Daurian steppe region is most intact example of an undisturbed steppe ecosystem and is also one of the last areas in the Palearctic that still support stable herds of larger vertebrates. The region has a distinct flora and fauna, with a number of endemic species.

6.2.2.2 Tropical and Subtropical Grasslands, Savannahs and Shrubland

Tropical grasslands also called savannahs have a tropical continental climate wherein wet and dry seasons come alternately. The grasslands existing intermixed with woody plants are designated as savannahs. These are located near the equator, between the Tropic of Cancer and the Tropic of Capricorn, and found in the interior part of continents between the tropical rainforests and tropical deserts. Grasslands and savannahs are of widespread occurrence within the subtropics and tropics. They cover much of Africa as well as large areas of Australia, South America and India. The term campos refers to grasslands or pastures of South America with vegetation cover comprising mainly grasses and herbs; scattered small shrubs and trees are occasionally found, generally near the banks of streams. The Llanos, located in the Orinoco River Basin, which runs between Colombia and Venezuela in northern South America, are some of the world's richest tropical grasslands. Termites are especially abundant in the tropical grasslands of the world. Savannahs in Africa have world's richest fauna of grazers and browsers (e.g. zebra and giraffe); there also occur predators such as lions.

6.2.2.3 Flooded Grasslands and Savannahs

These are large complexes that occur in the Everglades, Pantanal, Sahelian flooded savannahs, Zambezian flooded savannahs (*http://www.panda.org/about_our_earth/ecoregions/about/habitat_types/selecting_terrestrial_ecoregions/habitat09.cfm*) and flooded grasslands of Rann of Kutch, Gujarat, India. The Okavango Delta and associated flooded grasslands and savannah habitats constitute the Zambezian flooded savannahs. There are a rich diversity of birds and significant populations of the African elephants.

6.2.2.4 Montane Grasslands and Shrublands

These grasslands border the ‘cold deserts’ of the world. Such grasslands occur above the forest limit on the main mountain chains and in arctic latitudes. Climatic factors such as high winds and low temperatures interact to exclude trees. This major habitat type includes the Puna and Paramo in South America, subalpine heath in New Guinea and East Africa and the steppes of the Tibetan Plateau. The paramos of the northern Andes are the most extensive examples of this habitat type.

6.2.2.5 Other Types of Grasslands

In several areas, annual grasslands are important. In some instances, these have replaced perennial stands (e.g. North America), and in other instances, they are annual vegetation of desert and semi-desert areas. These are predominant where there is a Mediterranean climate with hot dry summers and wet, relatively warm winters.

In Europe, wood pastures are reported to be practised from Neolithic times (6000 BP) and can be found all over Europe. In this system, cattle are allowed to graze in forest. *Dehesa* (in Spain) and *Montado* (in Portugal) are other very old 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. These 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).

The extent of grasslands (including sown pastures and rangelands) as reported by FAO (2000) is given in Table 6.3. According to FAO (2000), 29.65% pastures are in Africa, 31.53% in Asia, 21.11% in America, 49.42% in Oceania and 8.25% in Europe.

6.2.3 Importance of Tropical Savannahs and Grasslands

Savannahs and grasslands dominate the tropical regions, covering approximately 20% of the global land surface (Scholes and Archer 1997; Parr et al. 2014). The tropical grassland biome is considered the cradle of human evolution in Africa (Beerling 2007), and an estimated 20% of the global human population depends

Table 6.3 Extent of pasture area in different continents of the world

Continents	Land area ('000 ha)	Pasture ('000 ha)	Per cent pasture
Africa	2,933,450	869,878	29.65
Asia	3,508,087	1,106,060	31.53
America	3,831,866	808,920	21.11
Europe	2,205,912	182,344	8.25
Oceania	848,729	419,455	49.42
World	13,004,202	3,442,078	26.47

Source: Grassland world statistical data, FAO (2000)—accessed on 15 September 2019 (www.fao.org/uploads/media/grass_stats_1.pdf)

directly on them for their livelihoods, including the use of uncleared lands for grazing, fuelwood, food and medicinal plants (Olsson and Ouattara 2013).

Tropical grasslands exist in India, East and West Africa and Central and South America. Many of the world's original grasslands have been largely converted to croplands or to seeded pastures. Still, these regions carry large number of grazing animals. Many of the world's original forests have been converted to grasslands. Many tropical types of grassland have a greater density of woody shrubs and trees as compared to that of temperate grasslands. Main areas of grasslands of South America include Llanos of the Orinoco Basin of Venezuela and Colombia, Cerrado of Brazil and Pine Savannahs of Belize and Honduras. The most threatened tropical savannah in the world is the Cerrado, a large region that occupies the centre of South America and is biologically rich (da Silva and Bates 2002). Both the Cerrado and the Llanos occur in South America, which represent complex habitats and exhibit high level of endemism in plants (da Silva and Bates 2002). It is also the second largest South American biome, and Cerrado is among the 36 terrestrial hotspots of biodiversity. In South America's grassland, the fauna is represented by animals like capybara, anaconda, armadillo, caiman and termites.

African savannahs cover 50% of the land area of the continent, characterized by diverse ecosystems such as densely wooded miombo woodlands and Serengeti grasslands with scattered trees. Savannahs provide water, grazing and browsing, food and fuel for tens of millions of people and have a unique biodiversity (Osborne et al. 2018). African savannahs are characterized by high diversity and abundance of large wild and domestic herbivores and their associated predators (Smithers 1983; Homewood 2008; Craigie et al. 2010). Ancient pastoral societies and their domestic herbivores (cattle, camels, donkeys, sheep and goats) have for thousands of years interacted with wild herbivores and often followed similar migration routes and seasonal foraging patterns (Homewood 2008; Fynn et al. 2016). Domestic herbivores are the only viable production alternative to crops in arid and semi-arid areas and play an important role in cultural practices (Homewood 2008). There is a high diversity of animals in the tropical grasslands especially in Africa. Over 40 different species of animals are found in African savannahs, some of which are eland, impala, wildebeest, plains zebra, rhinoceros, elephant, warthog, lion, leopard and cheetah.

Most tropical savannahs are dependent on frequent fires and megafaunal herbivory, which are essential for the internal ecological dynamics of savannahs, rather than externally imposed disturbances (Veldman et al. 2015; Fill et al. 2015). When fires are excluded and/or herbivores are not properly managed in savannahs, woody plants may rapidly increase in abundance (Veldman 2016). In addition to their distinct responses to altered fire regimes in terms of changes in the frequency, seasonality and/or intensity of fires, savannahs face the threat of conversion to agriculture and tree plantations (Laurance et al. 2014). The challenge for the ecological restoration of tropical savannahs is that they are fire-prone ecosystems that depend on fire for maintenance. The savannah restoration requires re-establishing the historical fire regime and the maintenance of vegetation structure and diversity as well as the ecological processes that depend on fire (Durigan and Ratter 2016; Honda and Durigan 2016; Abreu et al. 2017). Without fire, both old-growth and restored savannahs tend to become forests, which are possible alternative states in many parts of the world (Bond et al. 2005; Staver et al. 2011; Cava et al. 2017).

6.2.4 Grassland Types of India

Five major grass cover types of India have been recognized (Dabadghao and Shankarnarayan 1973) including *Sehima-Dichanthium* type, *Dichanthium-Cenchrus-Lasiurus* type, *Phragmites-Saccharum-Imperata* type, *Themeda-Arundinella* type and temperate-alpine grasslands. Grasslands generally occur in areas receiving between 250 mm and 900 mm annual precipitation (Singh and Gupta 1992). In India, the area under various kinds of grass cover, including fallow and wastelands, is estimated to be about 18% of the total land area. If the forested area (about 19% of total land) is included, most of which also supports grazing, and about 37% of land can be said to be available for grazing. The average annual production of dry grass or hay in India is about 250 million Mg. Most of the grasslands in India are of anthropogenic in origin and seral in nature because of the influence of livestock grazing, fire, deforestation, drought and abandonment of cultivation (see Singh and Gupta 1992).

There is a variety of grassland communities, with different dominants, in response to variability in environmental conditions including grazing, in each of the grassland type in India (Yadava and Singh 1977; Singh et al. 1979; Billore and Mall 1985; Singh and Gupta 1992). According to Rawat and Adhikari (2015), some important grasslands of India are alpine moist meadows of central Himalaya, alpine arid pastures of Transhimalaya, Terai grasslands of Gangetic and Brahamputra plains, floating grasslands of Manipur, Banni grasslands of Rann of Kutch in Gujarat and Shola grasslands of Western Ghats. Terai-Duar savannahs and grasslands occur in Southern Asia including Bangladesh, Bhutan, India and Nepal. These grasslands contain the world's tallest grasses (e.g. *Saccharum* or elephant grass) and have the greatest densities of tigers, rhinos and ungulates.

For more details regarding the distribution of species, climate and region, see Van Dyne et al. (1978), Singh and Gupta (1992) and Pathak and Dagar (2015).

6.3 Production Potential of Grasslands

Many studies have been reported on the standing crop and the rate of primary production and management of the grasslands throughout the world (Van Dyne et al. 1978; Singh et al. 1979; Singh and Gupta 1992; Pathak and Dagar 2015). Annual fresh biomass production of savannahs is reported to be about 30 Mg ha^{-1}; in a monsoon climate, an estimate for equatorial savannahs was found to be 12.5 Mg ha^{-1}, and Indian dry savannahs have annual increments of about 70 Mg ha^{-1} with green parts about 40%, perennial aerial parts 5% and roots 55%. Litter production in dry savannahs in India was found to be 7.5 Mg ha^{-1}. A mean of 7 Mg ha^{-1} year^{-1} net primary productivity for tropical grasslands and 5 Mg ha^{-1} year^{-1} for temperate grasslands was estimated. The annual aboveground

Table 6.4 Maximum value of standing biomass and productivity of some grasslands in India

Location	Grassland type	Biomass (Mg ha^{-1})		Production (Mg year^{-1})	
		AG	BG	AGNP	BGNP
Ambikapur	Mixed	4.23	–	4.36	5.63
Behrampur	*Cynodon dactylon*	11.72	19.92	5.71	13.61
Delhi	*Heteropogon contortus*	7.71	–	7.98	–
Jhansi	*Sehima nervosa-H. contortus*	16.34	3.33	10.19	4.97
Jodhpur	Mixed	1.64	7.80	1.64	5.70
Khirasara	Plain, ungrazed, mixed	4.19	2.05	2.01	1.55
Khirasara	Plain, grazed, mixed	1.87	1.60	0.98	2.47
Khirasara	Hilltop, grazed, mixed	1.14	0.52	0.83	0.96
Kurukshetra	Mixed	35.42	11.67	24.07	11.31
Pilani	Mixed	1.34	0.86	2.17	0.61
Ratlam	*Sehima nervosa*	9.54	8.73	4.33	3.99
Sagar	*H.contortus-Apluda mutica-Cymbopogon* martinii	15.23	13.81	9.14	9.37
Sambalpur	*Andropogon-Saccharum*	5.72	23.68	4.58	19.72
Udaipur	*Apluda*	2.71	4.08	2.56	2.55
Ujjain	Burned, mixed	13.67	10.63	–	–
Ujjain	Central grassland	10.74	9.20	–	–
Ujjain	*Dichanthium*	13.02	9.25	5.20	4.64
Varanasi	*Desmostachya* (upland)	25.05	7.88	22.18	13.77
Varanasi	*Eragrostis* (lowland)	34.48	12.82	33.98	11.61
Average		11.36	8.70	8.35	7.03

Source: Modified from Singh and Gupta (1992), who compiled from various sources

[a]Includes dead shoots and fresh litter, *AG* aboveground, *BG* belowground, *AGNP* aboveground net primary productivity, *BGNP* belowground net primary productivity

Table 6.5 Net primary production (NPP), biomass and carrying capacity of the world's grazing lands

Grassland biota type	Area (million km^2)	NPP GT C km^{-2} $year^{-1}$	[b]NPP Mg C km^{-2} $year^{-1}$	Biomass[a] Gt C	Carrying capacity AU km^{-2} (million AU)
Woodland shrub land	8.5	2.7	318	22	27 (230)
Savannah	15.0	6.1	407	27	27 (405)
Temperate grassland	9.0	2.4	267	6.3	27 (243)
[a]Agricultural land (tundra/ alpine meadow)	5.8 (8.0)	1.5 (0.5)	267 (63)	4.1 (2.3)	27 (157)
Desert shrub	18.0	0.7	39	5.9	3.9 (70)
Total	56.3	13.4	–	65.3	–(1105)

1 Gt = giggatonne = 1 billion metric tonnes
[a]An amount of land of the same NPP per unit area as temperate grassland has been added here to bring the total grazing land inventory up to the calculated 56.3 million km^2
[b]To compute NPP in Mg km^{-2} $year^{-1}$ of dry organic matter, the value should be multiplied by about 2, since plant dry organic matter is 45–50% carbon by weight

and belowground net primary production ranged from 0.83 and 0.61 to 33.98 and 19.72 Mg ha^{-1} $year^{-1}$, respectively (Table 6.4). The values for arid and semi-arid grasslands are lower than more humid grasslands.

Lieth and Whittaker (1973) reported 12.4 Gt C $year^{-1}$ of grassland totals, which tends to be on higher side as compared to other studies because of the reason that their studies were from undisturbed areas. It is evident from these results that the productivity of grassland (and so is capacity of grazing land) is strongly dependent on rainfall or access to water as illustrated by the high productivity of riparian habitats. For example, in the US Great Basin, all riparian lands cover fewer than 2% of the land area yet receive 50% of the livestock pressure. Jacobs (1991) also reported that the riparian meadows occupy only 1–2% of the interior north-west but account for 81% of forage removed by livestock. If one assumes that only the range currently being grazed is available for intensive management in the USA, herbage and browse could potentially be increased from 169 million to 220 Mg $year^{-1}$, and range grazing could be increased from 127 1 to 247 Mg $year^{-1}$ by upgrading poor, fair and very poor range to good range (Hair 1980). According to one estimate (http://home.alltel.net/bsundquist1/og2.html), the net primary productivity varies from 0.39 Mg C ha^{-1} $year^{-1}$ in desert conditions to 4.07 Mg C ha^{-1} $year^{-1}$ in savannah biotypes (Table 6.5).

In western North American temperate grasslands, aboveground primary production ranged from186 to 330,876 g m^{-2} $year^{-1}$ (Sims and Singh 1978), and net root production varied from 96 to 876 g m^{-2} $year^{-1}$. Total net primary productivity was 282 to 1203 g m^{-2} $year^{-1}$. About 34% and 81% of allocation of productivity was belowground in these temperate grasslands (Sims and Singh 1978).

Tropical savannahs can show remarkably high productivity, with a net primary productivity ranging from 1 to 12 Mg C ha^{-1} $year^{-1}$(Grace et al. 2006). The lower values are found in the arid and semi-arid savannahs occurring in extensive regions of Africa, Australia and South America. The global average of the tropical savannah productivity has been estimated to be 7.2 Mg C ha^{-1} $year^{-1.}$

Comparatively, the situation is very alarming in many other parts of the world. For example, in northern Africa, productivity of browse plants is only 150 kg DM km^{-2} mm^{-1}rain $year^{-1}$, of which 50% is actually consumed (Le Houerou 1980). This implies the absence of grass and a fairly desert-like environment. In central Soviet, 6–7 km^2 of grazing land are required per 100 sheep with capacity of 3 AU km^{-2}. In Latin America, it requires 15–50 km^2 of rangeland to support 100 cows with a capacity of 2 to 6 AU km^{-2} (WRI 1990). The situation in many other dry regions of the world is not different as mentioned above, and most of the rangelands are overgrazed and deteriorated. These need special management efforts.

6.4 Goods and Services of Pasture/Grazing Lands

Rangelands provide an array of ecosystem services such as food, fodder, fibre, medicinal plant, water and recreation and are important to the livelihoods of people across the globe, especially in developing countries. The most widespread use of grassland worldwide is in the production of domestic livestock (principally mammalian herbivores: cattle, sheep, goats, horses, water buffalo and camels). A large number of wild herbivores depend on grasslands and, in many cases, share the land with domestic herds. There is a large variety of forage plants, and for the most part, these are grasses or legumes. Semi-natural grasslands are significant source of many medicinal plants. These also store 10 to 30% of global soil organic carbon.

Grassland is a renewable resource; productivity is variable and determined by climate, soil and topography. Many studies have been reported on the standing crop and the rate of primary production of the grassland ecosystems (Van Dyne et al. 1978; Singh et al. 1979; Billore and Mall 1985; Singh and Gupta 1992; Pathak and Dagar 2015). Annual fresh biomass production of savannahs is reported to be about 30 Mg ha^{-1}; in a monsoon climate, an estimate for equatorial savannahs was found to be 12.5 Mg ha^{-1}, and Indian dry savannahs have annual increments of about 70 Mg ha^{-1} with green parts about 40%, perennial aerial parts 5% and roots 55%. Litter production in dry savannahs in India was found to be 7.5 Mg ha^{-1}. A mean of 7 Mg ha^{-1} $year^{-1}$ net primary productivity for tropical grasslands and 5 Mg ha^{-1} $year^{-1}$ for temperate grasslands was estimated. The annual aboveground and belowground net primary production ranges from 0.83 and 0.61 to 33.98 and 19.72 Mg ha^{-1} $year^{-1}$, respectively.

Besides provisioning services, the grassland systems provide many regulatory, supporting and cultural services that are important to humans. These include climate regulation, water storage, nutrient cycling, erosion control or soil stabilization, pollination and biodiversity (Table 6.6). Climate regulation via soil carbon storage and sequestration is highly valued. Temperate grasslands are the third largest global

Table 6.6 Grassland ecosystem services (based on MA (Millennium Ecosystem Assessment) 2005)

Provisioning services	Food
	Water
	Forage, livestock and biofuels
	Genetic resources
	Medicinal plants
Regulating services	Climate regulation (C-sequestration) Greenhouse-gas balance
	Flood prevention
	Regulation of water flows
	Water purification
	Soil erosion control and soil stabilization
	Maintenance of soil fertility including soil formation
Supportive services	Maintenance of genetic diversity
	Nutrient cycling, primary production, pollination
	Habitat and biodiversity
Cultural services	Recreation and tourism
	Religious value, educational values

store of carbon in soils and vegetation (after wetlands and boreal forests), and the amount of carbon that could be stored in the world's grazing lands is considerable and presents a potentially large climate change mitigation opportunity. The global potential for C sequestration in the soils of the world's grazing lands is 352 Tg CO_2 year^{-1} through improved grazing management in rangelands and pasturelands and the sowing of legumes in pasturelands (Henderson et al. 2015).

Ryan et al. (2016) have discussed the diversity and number of ecosystem services (supporting, regulating and cultural services) provided by miombo and mopane woodlands of Southern Africa. These critical resources provided food (wild fruits, tubers, nuts, edible insects, bushmeat), non-timber forest products for sale (e.g. honey, beeswax, insects), fuel (firewood and charcoal), construction materials (e.g. thatching grass, timber), water, nutrient cycling and medicinal plants. Recently, Rivera et al. (2019) studied GHG emissions from grasslands and bovine excreta in two intensive tropical dairy production systems and concluded that the intensive silvopasture system might contribute to the reduction of GHG emissions from grasslands in contrast to traditional grazing systems, despite the high stocking rates and legume densities, producing emissions similar to those of forest.

6.5 Degradation of Pasture/Grazing Lands

The Global Assessment of Soil Degradation (Oldeman et al. 1991) estimates that 680 million hectares of rangeland have become degraded since 1945, and Dregne et al. (1991) argued that 73% of the world's 4.5 billion hectares of rangeland is moderately or severely degraded. Degradation on rangelands can generally be described as a reduction in biological and economic productivity that occurs over a sustained period of time and is linked to improper or unsustainable human land uses and the subsequent impacts of this unsustainable use on vegetation composition, hydrology and soil processes (Bedunah and Angerer 2012). The causes of rangeland degradation are complex and are often combinations of factors rather than a single, identifiable factor. Land and livestock management, in conjunction with climate, are the main causes of rangeland degradation. These are commonly interrelated and are driven by contributing factors, such as government policy, land use changes, collection of fuelwood, land tenure, and economic conditions (Bedunah and Angerer 2012; Sivakumar and Stefanski 2007).

Natural factors such as fluctuating rainfall, rise in temperature and natural disasters and artificial factors (mainly anthropogenic) such as overgrazing, deforestation, over-exploitation, faulty methods of agriculture and industrial activities have led to degradation of pasturelands (Pathak and Dagar 2015). Dregne and Chou (1992) classified 6075.76 million ha area under irrigated land, rain-fed croplands, rangeland and hyper arid land throughout the globe, out of which 4556 million ha was reported under rangeland alone. Out of that, 3332 million ha (73%) were designated as moderate to severely degraded (Table 6.7). Bridges and Oldeman (1999) stated that 830 million ha land (198 m in Asia, 243 m in Africa, 68 m in South America, 9 m in Central America, 29 m in North America, 48 m in Europe and 83 m in Oceania) is degraded due to overgrazing. Other causative factors of human-induced land degradation (total 1995 million ha) include deforestation, agricultural mismanagement, over-exploitation and industrial activities. It is important to mention that the impact of human activities is uneven throughout the world and there can even be more factors of land degradation such as poisoning of underground water resources through excess use of pesticides and waterlogging due to faulty methods of irrigation.

Grasslands that are not overgrazed lose topsoil at a gross rate of about 100 Mg km^{-2} $year^{-1}$, about the rate of topsoil creation on grasslands. Topsoil erosion characterized by phenomena like gullies and arroyos loses soil at a typical rates of 40,000 Mg km^{-2} $year^{-1}$, though a significant portion of this is subsoil (http://home.altel.net/bsundquist1/og1.html).

Large-scale cattle ranching has resulted in the clearance of about 20 million hectares of Amazon rainforest during the 1980s, primarily in Brazil and Colombia. Cattle raising is also the main cause of rainforest conversion in Mexico and Central America. Stimulated by government incentives, most of the clearings are very large and poorly managed (Hecht and Cockburn 1989). The degradation of pastures is attributed to the introduction of grass species, such as *Panicum maximum* and *Hyparrhenia rufa*, not adapted to high soil acidity, low fertility, poor grazing management and invasion of better adapted weedy species. Phosphorus deficiency is a principal cause of low soil fertility leading to land degradation in pastures, and weed encroachment is an immediate consequence (Serrao et al. 1979). The end result of pasture degradation varies from pure weeds to almost barren land (Serrao and Homma 1993; Uhl et al. 1990). A pasture is degraded when weeds comprise more than 80% of the pasture biomass and the potential carrying capacity has decreased

Table 6.7 Extent of global land desertification (million ha) of rangelands

Continent	Total rangeland area	Degree of desertification				Total (moderate+)	Per cent desertified[a]
		Slight	Moderate	Severe	Very severe		
Africa	1342	347	274	716	5	995	74
Asia	1571	384	485	692	11	1188	76
Australia and New Zealand	657	296	277	55	29	361	55
Europe	112	31	27	52	1	80	72
North America	483	72	116	285	10	411	85
South America	391	94	88	194	15	297	76
Total	4556	1224	1267	1994	71	3332	73

[a]Slight degradation not included. Source: Modified from Dregne and Chou (1992)

from 1 to less than 0.3 animal units per hectare; the time required to achieve this stage of pasture decline varies between 7 and 15 years (Serrao and Toledo 1990).

Cattle production has long been an important cause of the loss of natural habitat and biodiversity in Latin America (Downing et al. 1992; Kaimowitz 1996; Murgueitio 2004). Pressure from expanding livestock production has resulted in large-scale deforestation in many areas. In addition to the environmental problems caused by the initial loss of forest, extensive grazing is often unsustainable. After an initial period of high yields, soil fertility is depleted and grass cover diminishes, resulting in soil erosion, contamination of water supplies, air pollution, further loss of biodiversity and degradation of landscapes. Lower income for producers results in continuing poverty and can lead to pressure to clear additional areas.

In Southeast Asia, many of the abandoned shifting cultivation fields are rapidly colonized by *Imperata cylindrica*, a coarse rhizomatous grass also known as *alang-alang* in Indonesia, *lalang* in Malaysia and *cogon* in the Philippines (Sanchez et al. 1992). The grass thrives on acid soils low in nutrients, reproduces by seeds and rhizomes, responds vigorously to burning and competes aggressively with other invaders. Except for young growth shortly after a burning, *Imperata* has very low palatability to cattle. On the other hand, *Imperata* provides sufficient ground cover to prevent soil erosion.

From perusal of the literature regarding the status of tropical grazing lands globally, it is evident that climatic reasons such as erratic and high intensity of rainfall leading to soil erosion, high evaporative demand and lack of moisture consequently effecting vegetative cover; edaphic factors such as impoverished soils having limited moisture storage capacity and poor infiltration in problem sodic soils; and anthropogenic and socio-economic factors such as increasing population, overstocking rates leading to overgrazing, fire, lack of fodder resources and uncontrolled grazing, faulty methods of forage cultivation and poor resource base of farmers are some important reasons which have led to degradation of rangelands.

The degradation of grazing lands is accelerating in developing countries. The scale of grazing land degradation has become so extreme that many workers recognize it as 'desertification' to describe it. Grazing animal populations tend to expand in parallel with human population, doubling every five decades. Carrying capacity of grazing lands decreases in parallel with topsoil loss, which in turn increases with increased bare soil and water run-off. Overgrazing by livestock is the principal cause of land degradation coupled with cutting of woody species in many countries where fuelwood is the major crisis. As a result of overstocking, grasslands are now deteriorating to the worst condition particularly in the developing world. Most degraded rangeland, worldwide, totals 860 million ha. In India also, degraded land and wastelands account for 120.72 m ha (ICAR and NAAS 2010). Tapping the productivity of this vast area depends on ruminants—cattle, sheep and goat—animals whose complex digestive systems enable them to convert roughage into food, including beef, mutton, milk and industrial materials (leather and wool). India too has a large animal population dependent upon these resources. According to an assessment of the Earth's dry land regions Dregne and Chou 1992, it was estimated that livestock production losses from rangeland degradation exceeded $23 billion (as in 1992).

In response to the needs for estimating the cost of grassland degradation to determine the cost of inaction and for identifying cost-effective strategies to address the consequent loss of livestock productivity, Kwon et al. (2016) developed a modelling framework where global statistics databases and remote sensing data/ analyses coupled with empirical/statistical modelling were designed to quantify the global cost of grassland degradation. By using the framework, they identified grassland degradation hotspots over the period of 2001 to 2011 and estimated changes in livestock productivity associated with changes in grassland productivity within the hotspots. Ignoring environmental benefits and losses in live weight of livestock not slaughtered or sold, the cost of livestock productivity was estimated about in 2007 US $6.8 billion. Therefore, it is important to restore these valuable resources to sustain the livelihood security of a population of millions.

6.6 Management of Pastures and Grazing Lands

The majority of the world's grasslands are considered to be degraded to some degree. Depending on the desired use, grasslands are managed for one of several goals, including production of forage for raising domestic and wild animals, carbon sequestration, biodiversity conservation, production of biofuels, enhancement of the environment or conservation of natural areas (Gibson 2009). Grassland management involves social, economic, cultural and technical factors. The grassland components are to be managed in way so as to obtain the optimum combination of goods and services for society on a sustained basis. Many natural areas require management intervention because natural disturbance regimes have been disturbed or no longer in place in highly degraded grasslands. The following approaches may help in the management of these lands particularly in degraded and problem areas:

6.6.1 Protection from Grazing

Most of the grasslands in arid and semi-arid areas are overgrazed (Fig. 6.1). When the same grassland is protected from grazing, the productivity is increased manyfold. Based on a well-conducted study in savannahs of Central India, Billore and Mall (1985) while reporting dry matter budget for different grazing lands mentioned total net production of 20.34, 13.33, 12.83 and 11.64 Mg ha^{-1} year^{-1} in a zero (protected)-, light (19 cattle per ha annually)-, moderate (41 cattle per ha)—and heavy (50 cattle per ha)-grazed grasslands, respectively. The total aboveground net production was 14.08, 9.28, 6.53 and 4.54 Mg ha^{-1} year^{-1}, respectively, while total belowground net production was 6.26, 4.05, 6.30 and 7.10 Mg ha^{-1} year^{-1}, respectively, from these grasslands. Dagar and Mall (1980) observed that the number of palatable species increases when fenced and total number of species increases adding to organic matter in soil and improving the water holding capacity,

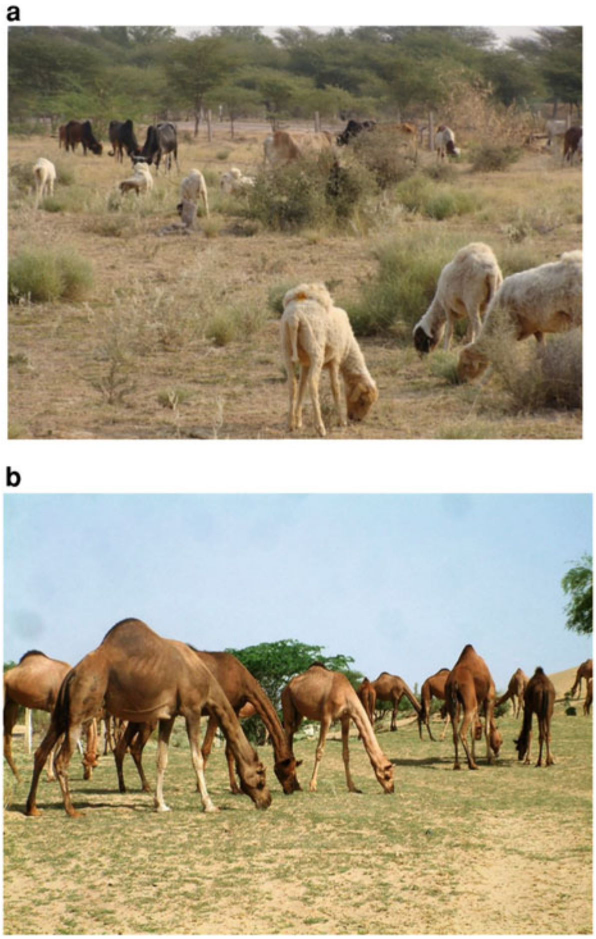

Fig. 6.1 Traditional overgrazed rangelands in arid regions of Rajasthan in India: (**a**) cattle and goats (**b**) camel-herd

infiltration rate and nutrients into the soil. The soil properties of problem soils including alkali soils in terms of soil pH, organic matter, available nutrients and the biological activity (microorganism) are improved when grasslands are protected from grazing. These should be managed according to their carrying capacity. In some situations, light grazing may increase productivity (Kumar and Joshi 1972; Barrett-Lennard 2003); hence, controlled grazing may help in sustaining the productivity of grazing lands.

A highly grazed land on alkali soil is very poor in its productivity. Grasses such as *Sporobolus marginatus* and *Desmostachya bipinnata* and saltbushes like *Kochia indica* and *Suaeda fruticosa* are poor in palatability. Salt-tolerant woody perennials such as *Capparis decidua*, *Salvadora oleoides* and *Ziziphus nummularia* are frequent. *Prosopis juliflora* with stunted growth has colonized in many sodic regions of Indian subcontinent. In many saline basins, halophytic species are found which are very poor in their palatability. At many localities, the aboveground biomass of the

Table 6.8 Effect of long-term fencing of grazing land on soil status on highly alkali soil

	Soil parameters							
	Original alkali soil				After 15 years of protection			
	pH	Org C	Na	Ca + Mg	pH	Org C	Na	Ca + Mg
Soil depth (cm)	(1:2)	(g kg^{-1})	(Per cent of exchangeable cations)		(1:2)	(g kg^{-1})	(Per cent of exchangeable cations)	
0–15	10.6	2.4	91	6	8.6	4.6	20	70
15–30	10.2	2.0	90	7	9.0	3.4	28	59
30–60	9.9	1.4	79	13	9.5	2.1	54	32
60–90	9.5	1.2	62	30	9.4	1.6	50	39

Modified from citation of Pathak and Dagar (2015)

entire community is found to range from 0.2 to 0.8 Mg ha^{-1}. When protected from grazing, one sodic field (pH >10) mostly predominated by *Sporobolus marginatus* grass having herbage biomass production of 0.25 Mg ha^{-1} produced 2.6 Mg ha^{-1} forage biomass after 2 years of protection. This biomass increased every year of protection. Effect of long-term fencing showed that the number of palatable species such as *Dichanthium annulatum*, *Cynodon dactylon*, *Bothriochloa pertusa* and *Chloris gayana* increased significantly and soil improved in terms of reduction in pH and increase in organic matter and exchangeable cations (Table 6.8). More leguminous species appear in the range, which enhance the quality of fodder. Singh et al. (1979), Dagar and Mall (1980), Dagar (1987a-c), Singh and Gupta (1992), El-Keblawy (2003) and Pathak and Dagar (2015) also reported that the protection of grazing lands from anthropogenic factors led to increase in total number and also palatable species, plant cover and productivity.

Dagar and Mall (1980) studied the vegetation of Kshipra ravines in detail and observed that when protected many species of grazed fields disappeared while many new appeared. In highly eroded field, species such as *Heteropogon contortus*, *Themeda triandra*, *Cymbopogon martinii*, *Ischaemum rugosum*, *Tragus biflorus*, *Thelepogon elegans*, *Alysicarpus rugosus*, *A. longifolius*, *Achyranthese aspera*, *Polygala chinensis*, *Setaria glauca*, *Euphorbia geniculata*, *Rhynchosia capitata*, *Rungia repens*, *Peristrophe bicalyculata*, *Paspalidium flavidum*, *Justicia diffusa*, *Striga euphrasioides*, *Phaseolus trilobus*, *Laugascia mollis*, *Scleria stocksiona* and *Solanum nigrum* were found restricted to protected fields, or if found in grazed fields were only occasional. Species such as *Oldenlandia corymbosa*, *Sporobolus coromandelianus*, *Tridax procumbens*, *Eragrostis pilosa*, *E. tenella*, *Cynodon dactylon*, *Enicostema verticillatum*, *Evolvulus alsinoides*, *Convolvulus pluricaulis*, *Cassia tora*, *Ocimum americanum*, *Iphigenia indica*, etc. occurred in grazed fields only or very occasionally in protected fields. A relatively high plus value for grazing susceptible number (GSN) indicates that the species has some disadvantage under grazing, while conversely a relatively high minus value indicates that the species is benefited from grazing. *Bothriochloa pertusa*, *Chrysopogon fulvus*, *Iseilema laxum*, *Heylandia latebrosa*, *Rhynchosia minima* and *Euphorbia hypercifolia* had more

Table 6.9 Grazing susceptibility number (GSN) of some species found in ravines

Species	GSN[a]	Species	GSN
Bothriochloa pertusa	−6	*Dichanthium annulatum*	+1
Chrysopogon fulvus	−6	*Alysicarpus monilifer*	+1
Iseilema laxum	−5	*Cyperus rotundus*	+2
Euphorbia hypercifolia	−7	*Apluda aristata*	+3
Heylandia latebrosa	−6	*Crotolaria medicaginea*	+5
Rhynchosia minima	−6	*Biophytum sensitivum*	+6
Euphorbia hirta	−5	*Euphorbia thymifolia*	+7
Indigofera linifolia	−4	*Sehima nervosum*	+7

Density of species in ungrazed pasture—Density of species in grazed pasture
[a]GSN = −---

Density in ungrazed when numerator is positive or density in ungrazed when numerator is negative

Fig. 6.2 Stabilization of ravines by natural vegetation after long protection from grazing (Photo by Yaduvendra Singh; Source Dagar 2018a)

importance value index (IVI) (for details, see Dagar 2018a, b) and high negative GSN (Table 6.9), showing grazing resistance. Species such as *Apluda aristata* and *Sehima nervosum* benefited maximally from protection, while *Dichanthium annulatum*, *Alysicarpus monilifer* and *Cyperus rotundus* were less affected by grazing.

Overgrazing of eroded habitats such as ravine lands has drastic impact on root development, particularly of grasses, which play a key role in soil binding. Protection from grazing and selective harvesting helped a lot in improving root development and biomass production in these habitats (Dagar 1987a, b, 1995a). When the area is closed from grazing, the natural succession takes place, and more palatable species appear and establish replacing the grazing-resistant species (Fig.6.2). Where possible, natural vegetation with well-developed root mats should be established

Table 6.10 Belowground biomass (Mg ha^{-1}) at different depths of soil as measured in July (values as mean ± SE); values in parenthesis denote the percentage of total root biomass

Field condition	0–10 cm	10–20 cm	20–30 cm	>30 cm
Protected	7.72 ± 0.83 (48.4)	4.52 ± 0. 61 (28.3)	2.47 ± 0.34 (15.5)	1.25 ± 0.26 (7.8)
Grazed	0.23 ± 0.07 (54.8)	0.16 ± 0.02 (27.1)	0.06 ± 0.01 (13.2)	0.02 ± 0.06 (4.9)

Source: Modified from Dagar (1987a, 2018a)

after protection from grazing in disturbed concentrated flow zones affected by gully erosion (Sidorchuk and Grigorev 1998; Dagar 2001; Morgan and Mngomezulu 2003). In doing so, soil loss and sediment production will be cut down, and the connectivity in the landscape will be interrupted resulting in a smaller sediment delivery to valley bottoms or river channels.

On an average, 9.38 and 1.59 Mg ha^{-1} aboveground biomass and 5.87 and 2.37 Mg ha^{-1} belowground biomass were observed in protected and grazed ravine areas, respectively, in upper 30 cm soil depth (Dagar 1987a), and it was further observed that in July (rainy season), about 78.7 and 81.8% of total belowground biomass were restricted to 20 cm of soil in protected and grazed plateau, respectively, and the belowground biomass reduced abruptly in grazed field as compared to protected (Table 6.10).

The above—and belowground biomass in protected and grazed fields was maximum in rainy season and minimum in summer, hence mainly depending upon rainfall and temperature and phenology of the species. The relationship between biomass and rainfall and temperature in protected and grazed fields was found to be as follows:

$$Y_1 = 2252.5844 + 4.1091\ X_1 - 69.0075\ X_2 (R^2 = 0.41; p \leq 0.05)$$
$$Y_2 = 428.7562 + 0.8341\ X_1 - 14.1307\ X_2 (R^2 = 0.69; p \leq 0.05)$$
$$Y_3 = 967.6142 + 2.1771\ X_1 - 23.7078\ X_2 (R^2 = 0.65; p \leq 0.05)$$
$$Y_4 = 483.4168 + 1.0306\ X_1 - 13.9081\ X_2 (R^2 = 0.64; p \leq 0.05)$$

where Y_1 and Y_2 are aboveground biomass (g m^{-2}) in protected and grazed fields, respectively; Y_3 and Y_4 are the corresponding belowground biomass values; X_1 is rainfall (mm per month); and X_2 is mean temperature (^{0}C mean daily).

For more details about the structure and succession of vegetation in grazed and protected rangelands, see Pathak and Dagar (2015) and Dagar (2018a, b).

6.6.2 Control Grazing (Cut-and-Carry System)

In series of experiments conducted by Pande and Singh (1985), Dagar (1987b) and Trivedi (2001), it was revealed that frequent grazing and clipping (at various heights) reduced the total biomass production and deteriorated the soil as compared to control conditions (protected grasslands). Therefore, rangelands can be successfully managed sustainably through long intervals of cuttings or control grazing following the principal of carrying capacity. In could be possible to produce more aboveground biomass under selected cuttings of natural grasses like *Dichanthium annulatum*, *D. caricosum*, *Iseilema laxum*, *Chrysopogon fulvus*, *Sehima nervosum* and *Heteropogon contortus* and also legumes like species of *Stylosanthes*, *Calopogonium*, *Clitoria* and *Phaseolus* (Dagar 1987b, 2018a, b).

Although clipping does not simulate grazing precisely, an appreciation of grazing responses can be obtained by imposing clipping treatments. Therefore, different frequencies at different heights of clipping reveal the change in the herbage and subterranean biomass of plant species particularly in grasses (Caughenour et al. 1984; Pande and Singh 1985), and this may help in managing grazing in rangelands. Dagar (1987b) experimented during rainy season taking nine grasses found growing in ravines of different strata and clipped at different heights (depending upon the stratum of a species) and intervals of time (15, 30 and 45 days initiating after 2 months of establishment; thus clipped six, three and two times, respectively, during 5 months of growth). Of these species, *Dichanthium caricosum*, *D. annulatum*, *Chrysopogon fulvus* and *Sehima nervosum* produced more above-ground dry matter under selected conditions of clipping as compared to unclipped, while in other species, the aboveground biomass decreased and it varied with species and frequency of clipping.

Belowground biomass decreased in each case except one treatment in *S. nervosum*. The correlation coefficient between clipping frequency and shoot and root biomass was found to be significant at $p \leq 0.05$. The reduction in total biomass was more than 50% when clipped at the interval of 15 days (representing frequent grazing) in *D. annulatum*, *D. caricosum*, *Themeda triandra* and *Iseilema laxum*, while in other grasses tested, it was less than 50%. The frequent clipping (grazing) and consequent recovery allow little time for the manufacture of photosynthates; hence, downward translocation is limited resulting in the reduction in biomass production. Moreover, during this time, the earlier accumulated total non-structural carbohydrates in these organs are utilized internally to support their maintenance respiration, which may be enhanced due to wounding effect (Evans 1972) and the increased exudation losses (Bokhari and Singh 1974). In one study, Edroma (1985) observing the effects of clipping on *Themeda triandra* and *Brachiaria platynotan* found that the clipping stimulated tillering and yield but later depressed them, severely when cut fortnightly at lower heights. Dry matter production in both shoots and roots increased with rising clipping heights and interval, and in all the observed species, root/shoot ratio of unclipped plants was higher than the clipped ones. In many parts of the world, successful cut-and-carry systems have been developed successfully.

6.6.3 Application of Fertilizers and Amendments

Most of the grasslands are very poor in nutrition and so in productivity. If a small dose of fertilizers is applied, the productivity increases significantly. Rai and Kanodia (1981) observed that application of 60 kg N ha^{-1}as ammonium sulphate was the most economic dose for maximum forage production from *Sehima-*

Heteropogon grassland as compared to urea, calcium ammonium nitrate (CAN) and FYM. The increase in the dry matter yield due to ammonium sulphate was 15, 7 and 27% higher than the yield obtained with the application of urea, CAN and FYM, respectively. This source of nitrogen also increased the cover of desired species *Sehima nervosum* which was much lower in the control. Further, application in three equal split doses at 25 days' interval from the onset of monsoon was superior in respect of higher forage production and crude protein yield over single dose or two split doses of nitrogen. Third week of July was found to be the most suitable for fertilizer application as compared to other periods. In one trial in Andamans, when fertilizers were applied in natural grassland at 50 kg N, 30 kg P_2O_5 and 30 kg K_2O ha^{-1}, there was forage yield of 6.6 Mg ha^{-1} as compared to 2.1 Mg ha^{-1} without any fertilizer during first year itself (Sharma et al. 1991, 1992), and both forage production and quality of grasses in terms of per cent crude protein were improved considerably by application of nitrogen. Trivedi (2001) also found that application of nutrients (nitrogen and phosphorus) showed a considerable increase in herbage production in selective grazing. Nitrogen alone (40 kg ha^{-1}) exhibited average increase of 28% in yield, while corresponding value for phosphorus (25 kg ha^{-1}) was 22%. Application of nitrogen and phosphorus increased pasture production in north-west Himalayan grazing lands (Sharma and Karanne 1988) and arid and semi-arid regions of Western India (Tewari et al. 2014). In one study conducted in Central India, application of 40 to 60 kg N ha^{-1} and 20 to 30 kg P_2O_5 ha^{-1} increased pasture production by 50 to 100% in majority of grasses tested, and crude protein contents increased considerably (Pathak and Dagar 2015).

In problem soils, application of suitable amendments increases the production of forages to greater extent. For example, in alkali soils (pH >10, ESP 94), application of gypsum significantly increased the yield, more so with the passage of time, and also influenced soil properties (increase in infiltration rate, reduction in pH and ESP, increase in organic carbon and exchangeable cations). Kumar (1988) confirmed these facts in five tropical grasses (*Leptochloa fusca*, *Panicum laevifolium*, *P. antidotale*, *Chloris gayana* and *Cynodon maritimus*) on an extremely sodic soil.

6.6.4 Use of Saline Water in Water-Scarce Areas

In most of the arid and many semi-arid regions of the world, the underground water is saline. During dry period, there is drastic scarcity of fodder, and the people lead the nomadic life taking their herds away in search of fodder. It is quite feasible to increase the production of the grazing lands of these regions using saline water judiciously and cultivating improved species of grasses with saline water. It was found that in north-western India in low rainfall areas (~450 mm), the grazing lands are on calcareous saline soils and are very poor in yield (average forage biomass of 0.85 Mg ha^{-1} in grazed conditions and about 2.4 Mg ha^{-1} when protected from grazing), but when applied with one or two irrigations with saline water during March to May, these produced 3.5 to 4.0 Mg ha-1 forage in July. The forage could be harvested any time during dry period. Further, selected improved species were

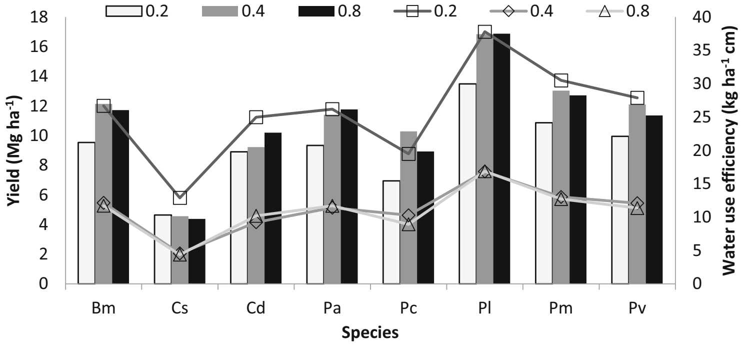

Fig. 6.3 Dry biomass yield (bars) and water use efficiency (lines) of different grasses when irrigated with different Diw/CPE ratio of saline water. Grass species: Bm Brachiaria mutica, Cs *Cenchrus setigerus*, Cd *Cynodon dactylon*, Pa *Panicum antidotale*, Pc *P. coloratum*, Pl *P. laevifolium*, Pm *P. maximum*, Pv *P. virgatum*. (Source: Tomar et al. 2003a, b)

cultivated using saline water (ECiw 8–12 dS m^{-1}) producing dry biomass up to 17 Mg ha^{-1}. In one experiment conducted on sandy loam soils in dry regions of India irrigating with water of high salinity (ECiw 10 dS m^{-1}) in different Diw/CPE ratio of irrigation water, Tomar et al. (2003a, b) found that forage grasses like *Panicum laevifolium* and *P. maximum* were the most suitable species producing annually 14–17 Mg ha^{-1} dry forage (Fig. 6.3) showing their potential as silvopastoral grasses if grown in protected conditions.

Malik et al. (1986) reported that *kallar* grass (*Leptochloa fusca*) grown on salty soil and irrigated with brackish water could produce 50 Mg ha^{-1} $year^{-1}$ fresh biomass in Pakistan. 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. Qadir et al. (2002) 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*. Dagar and Minhas (2016) have compiled extensive information on the use of saline and other poor-quality waters in different agroforestry systems across different regions of the world.

6.6.5 Integrating Perennial Pastures into the Grazing Farm

In Australia and many other regions where major farm economy is based on livestock, perennial pastures are often a source of green feed at a time when other feed is limited. Carrying stock through periods of feed scarcity is difficult and expensive and limits profits from livestock production. Therefore, integration of perennial pastures with species of high productivity is very important. These not only address a seasonal feed gap, protect stocking and increase income of stakeholders but also provide environmental benefits such as increased water use, which reduces waterlogging and groundwater recharge. Reducing recharge then helps prevent or delay the onset of dryland salinity (Moore et al. 2006).

Growing lucerne (*Medicago sativa*) in the Central Wheatbelt of Australia (annual rainfall 370 mm with 80% falling between April and October; soil types include deep sands and shallow duplex soils) is an example of successful intervention when lambing was more profitable in July (optimum area of Lucerene) than in May. Further, growing of mixture of perennials was compared on south coast in Australia raising annual pasture, lucerne, kikuyu (*Pennisetum clandestinum*) and a summer-active tall fescue (*Festuca arundinacea*) feeding two livestock systems—a self-replacing Merino flock for wool production only and a self-replacing Merino flock using excess ewes for crossbred lamb production. It was found that the high-quality perennial pastures are best used in a livestock system that focuses on meat production rather than on one based on mostly wool production and were more economical as compared to annual pastures. For both flock types, there was an increase in stocking rate and pasture use and growth and a decrease in supplementary feeding (Table 6.11).

There are persistent problems of waterlogging soil salinity and also acidity and wind erosion in Australia; hence, it is difficult to sustain with annual pastures or arable agriculture. To minimize these problems, interventions of perennial pastures consisting of salt-tolerant species are getting popularity as is evident with the fact that the area of lucerne increased from ~5000 ha in 1995 to about 170,000 ha in Western Australia in 2001 (Moore et al. 2006). Among the choices of species include saltbushes (*Atriplex*) to reduce salinity of soil and tagasaste or tree lucerne (*Chamaecytisus proliferus* var. *palmensis*) as wind break; highly salt-tolerant grasses such as saltwater couch (*Paspalum vaginatum*), *Puccinellia ciliata*, tall wheatgrass (*Thinopyrum ponticum/elongatum*) and legume strawberry clover (*Trifolium fragiferum*); moderately tolerant grasses like *Phalaris aquatica*, *Festuca arundinacea*, *Pennisetum clandestinum* and *Sporobolus virginicus*; and legume fodder *Trifolium balansae/michelianum*. These days, acid-tolerant and grazing-tolerant lucerne varieties have been developed. Perennial herbs like chicory (*Cichorium endivia*) with new varieties and perennial legumes like sulpha (*Hedysarum coronarium*) and new, warm season grasses specifically developed for southern Australia. Thus, there is strong interest in perennial pastures particularly in Western Australia due to non-sustainability in annual pastures and crops due to waterlogging, salinity, soil acidity and wind erosion. The potential production benefits from perennial pastures include (Moore et al. 2006) out-of-season green feed, increased carrying capacity, ability to reduce or replace supplementary feeding in autumn, ability to increase production from degraded land with a low carting capacity, ability to turn off animals at target live weights all year-round, reduced wool faults and maintenance of wool fibre diameter and staple length, reduced

Table 6.11 Profit and production parameters for optimum management with three different pastures

Parameters	Flock type I			Flock type II		
	Annual pasture (AP) only	AP + lucerne + kikuyu	AP + lucerne + kikuyu + tall fescue	Annual pasture (AP) only	AP + lucerne + kikuyu	AP + lucerne + kikuyu + tall fescue
Profit ($\$year^{-1}$)	19,900	79,900	86,200	64,300	138,800	164,500
Stocking rate (DSE/WG ha)	8.1	10.7	10.1	8.5	10.0	12.0
Supplement feeding (kg DSE^{-1})	18.5	8.3	6.9	33	8.3	8.4
Lambing (%)	87	92	92	89	92	92
Area annual pasture (% of farm)	70	25	19	70	23	3
Area perennial pasture (% of farm)	0	45	51	0	47	67
Pasture growth (Mg ha^{-1})	6.6	7.0	7.2	7.1	7.6	7.5
Pasture utilization (%)	35	46	47	37	45	50

Flock I: self-replacing Merino flock for wool only; flock II: self-replacing Merino flock with crossbred lamb production; WG, winter-grazed Source: Moore et al. (2006)

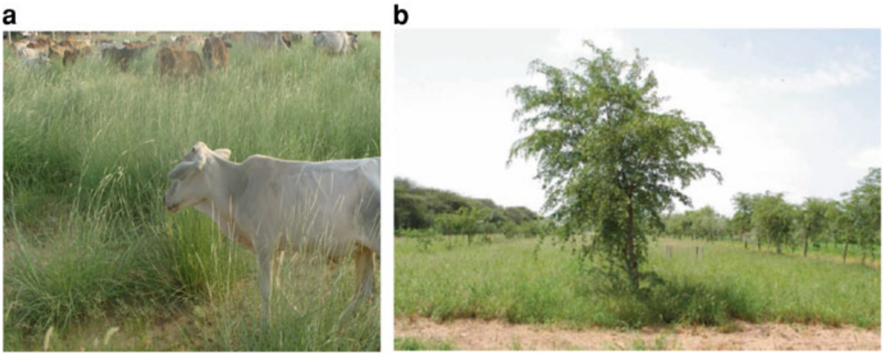

Fig. 6.4 (**a**) Successfully seeded improved grasses in grazing lands of dry regions in Indian subcontinent; (**b**) silvopasture system with *Colophospermum mopane* (Photo: ML Soni)

fodder conservation, increased winter feed and soil conservation benefits such as increased water use and reduced deep drainage to groundwater, maintenance of plant cover in summer to reduce wind erosion and increased perennial cover for waterways.

In dry regions of Indian subcontinent, many natural grasses have been improved and introduced or seeded successfully in grazed lands (Fig. 6.4). Some important high-yielding cultivars of perennial grasses are *Cenchrus ciliaris*, *C. setigerus*, *Lasiurus sindicus*, *Dichanthium annulatum*, *Panicum antidotale*, *P. turgidum* and *Sporobolus marginatus*. Among pasture legumes, *Lablab purpureus* showed good compatibility with *L. sindicus* and *C. ciliaris*. Some top feed species which are compatible and in optimum density for balanced production from understorey and upper storey of the silvopasture development in arid region include *Albizia lebbeck*, *Tacomella undulata*, *Colophospermum mopane* (Fig. 6.4a & b), *Acacia senegal*, *Ziziphus numularia* and *Z. rotundifolia*. These systems are quite sustainable under control grazing.

6.6.6 Introduction of Trees of Nutrient Value on Grazing Lands

Trees do improve site conditions in grasslands by adding organic matter and nutrients through leaf-fall, by reducing soil temperatures and water loss due to evapotranspiration and by attracting birds and large mammals that add nutrients to the soil in their droppings. Chen et al. (1992) reported the importance of trees and shrubs on grazing lands of Asia and Pacific region. In areas of tropical rainforests, species of *Gliricidia*, *Fleminga*, *Erythrina*, *Leucaena*, *Tephrosia*, *Albizia*, *Pongamia* and *Sesbania* are predominant as shade trees in pastures. In wet and dry regions of Thailand and Indian subcontinent, species of *Leucaena*, *Tamarindus*, *Acacia*, *Gliricidia*, *Sesbania*, *Dalbergia*, etc. are common in savannahs. In semi-arid and arid steppe of Indian subcontinent, species of *Acacia*, *Prosopis*, *Ziziphus*, *Ficus*, *Cordia*, *Azadirachta* and many halophytes are common. In subtropical China, more than 400 species of fodder trees and shrubs are found naturally as well as introduced in pastures. Leaves of *Populus*, *Salix*, *Ulmus*, *Robinia* and many others are used in feeds. *Acacia* (*catechu*, *nilotica*, *sieberina*), *Manihot esculenta*, *Calliandra calothyrus*, *Erythrina variegata*, *E. burana*, *Ficus benghalensis*, *F. religiosa*, *Gliricidia sepium*, *Artocarpus heterophyllus*, *Albizia lebbeck*, *Leucaena leucocephala*, *Cajanus cajan*, *Prosopis juliflora*, *P. glandulosa*, *P. cineraria*, *Sesbania grandiflora*, *S. sesban*, *Tamarindus indica*, *Trema tomentosa*, *Moringa oleifera*, *Simarouba amara*, *Tephrosia vogelli*, *Gmelina arborea*, *Jessenia bataua* and *Ziziphus mauritiana* are widely used in Asia and Pacific regions as fodder trees. Geng et al. (2017) reported prioritizing of fodder tree and shrub species based on traditional knowledge and experimentation with mithun (*Bos frontalis*) browsing in natural conditions in China. They listed 142 species of wild forage plants belonging to 58 families. *Debregeasia orientalis*, *Saurauia polyneura* and *Rubus lineatus* are among the most preferred species by mithun.

In North Africa, shrublands consisting of fodder trees and grasslands cover an area of 940,000 km^2 of which 65,000, 35,000 and 25,000 km^2 are located in semi-arid, arid and desert regions (Le Houerou 1989). Grazing represents 60 to 80% of the economic outputs of North African shrublands, and contribution of native fodder shrubs to the animal diets is more than 70%. The main fodder trees in semi-arid and humid ecosystems are *Fraxinus xanthoxyloides*, *Quercus rotundifolia* and *Juniperus oxycedrus* and among shrub species of *Cytisus*, *Globularia*, *Ormenis*, *Genista* and *Thymus*. In many areas of steppe vegetation, salinity is predominant. Crassulescent steppe consists of species of *Salsola*, *Suaeda*, *Arthrocnema* and *Salicornia*. Nanophanerophytes include species of *Ziziphus*, *Atriplex*, *Calligonum* and *Tamarix*. In areas with rainfall of 200 mm, *Artemisia herba alba*, *A. campestris* and *Medicago arborea* are predominant (Aich 1987). *Acacia sieberiana*, *A. Mangium*, *Gliricidia sepium*, *Ficus* spp., *Trichanthera gigantea*, *Erythrina glauca*, *E. edulis*, *Leucaena leucocephala*, *Samanea saman*, *Cordia dichotoma*, *Antidesma bunius*, *Manihot utilissima*, *Sesbania sesban* and *Spondias mombin* are the trees of high impact in humid Africa. Devendra (1992) listed 124 important fodder trees in dry tropical Africa and also reported the nutritional potential of prominent trees and shrubs as protein source in ruminant nutrition (Table 6.12). The crude protein contents of many of these feeds (*Manihot esculenta*, *Calliandra calothyrsus*, *Erythrina variegata*, *Leucaena leucocephala* and *Cajanus cajan*) are quite high in the range of 22.2 to 25.8%.

In areas with rainfall of about 250 mm, *Acacia senegal*, *A. nilotica*, *A. raddiana*, *A. tortilis* and species of *Adansonia*, *Balanites*, *Commiphora*, *Salvadora* and *Guiera* are predominant; the main species in areas with a rainfall around 440 mm include *Acacia laeta*, *A. seyal*, *A. tortilis* and *Balanites roxburghii*, while in areas with rainfall of about 600 mm, *Faidherbia albida*, *Pterocarpus lucens*, *Tamarindus indica*, *Dobera glabra* and *Ziziphus mauritiana* are predominant.

Belsky et al. (1993) reported that where grazing intensity was low to moderate, the areas under tree crowns had a unique understorey flora and higher biomass, lower bulk density and higher levels of P, K, Ca and mineralizable N than open grasslands. However, in heavily grazed areas, differences were few showing that if grazing

Table 6.12 Nutritional characteristics of principal tree fodders and shrubs

Species	DM (%)	Per cent DM basis CP	CF	EE	Ash	ME (MJ kg^{-1})	Ca (%)	P (%)
Acacia catechu, A. nilotica, A. siberin	29.0	15.1	22.6	8.9	8.2	8.4	1.21	0.06
Manihot esculenta	21.1	24.2	15.6	4.0	6.6	14.4	2.62	0.22
Calliandra calothyrsus	26.4	24.0	21.7	2.4	8.0	12.6	1.6	0.2
Erythrina variegata	32.0	25.8	17.4	5.8	6.7	14.3	–	–
Ficus exasperata, F. benghalensis, F. religiosa	17.0	14.0	22.4	4.5	5.8	12.0	1.31	0.17
Gliricidia sepium, G. maculata	25.0	14.7	19.9	5.4	4.7	12.84	1.58	0.29
Artocarpus heterophyllus	36.6	14.0	22.1	3.8	11.5	14.2	1.46	0.15
Leucaena leucocephala	30.0	22.2	19.6	6.9	4.4	12.1	0.27	0.12
Cajanus cajan	25.2	22.8	20.1	5.6	5.8	13.4	0.37	0.17
Prosopis cineraria	23.4	14.0	17.8	1.9	6.8	11.2	2.73	0.15
Sesbania grandiflora, S. sesban	18.0	22.6	18.4	2.1	9.3	13.6	1.48	0.34
Tamarindus indica	28.0	14.0	21.0	4.6	8.6	14.4	2.81	0.20

CP crude protein, *CF* crude fibre, *EE* ether extract, *ME* metabolizable energy, *DM* dry matter
Source: Compiled from various sources (www.fao.org/3/T0632E07.htm; retrieved on 24-07-2019)

pressure is reduced, the positive effect of tree canopy will be obvious. Tree species such as *Salvadora oleoides*, *S. persica*, *Capparis decidua*, *Acacia nilotica*, *A. leucophloea*, *Prosopis cineraria* and now *Prosopis juliflora* are the most frequent on common community grazing lands in India.

In coastal areas, coconut is most common tree on pasturelands. Cattle raising usually involves grazing on these pastures. An organized form of this natural vegetation as silvopasture assures 10 Mg ha^{-1} $year^{-1}$ biomass production (as against 1 Mg ha^{-1} $year^{-1}$ from natural stands) at 10-year rotation in dry zones besides assuring soil conservation, healthy environment and employment generation (Pathak et al. 1995). The role played by *Prosopis cineraria* in dry ecologies of India and by *Faidherbia albida* in Africa is now well-established in sustaining the yield of both crops and forages and also ameliorating the soil. While explaining the nature of grassland dynamics and their management, Dagar and Pathak (2005) gave comprehensive information when trees play crucial role in the management of grazing lands. Based on long-term studies, Rai (2012) reported the role played by many multipurpose trees such as *Ailanthus excelsa*, *Acacia tortilis*, *Hardwickia binata* and *Lencaena leucocephala* in pastoral systems for livestock production. Until relatively recently, these feed resources have been generally ignored in feeding systems for ruminants, mainly because of inadequate knowledge on various aspects of their potential use. Out of these trees and shrubs, nitrogen-fixing leguminous trees are important for their high nutrient value as protein sources and also for their nitrogen-fixing ability in soil. Villanueva-Partida et al. (2019) recognized the value of traditional uses of dispersed trees in the pastures of the mountainous region of Tabasco, Mexico, and listed 64 such trees which can be promoted for growing in these pastures.

6.7 Silvopastoral Systems for Degraded Pasture/Grazing Lands

Silvopasture, as an integrated land use practice that combines trees, forage and livestock, has been in existence for millennia. There are many variants of this land use in both the temperate and tropical regions of the world practised at small and large scales. Modern silvopasture, however, is not just a new name for an old practice; it is rooted in sound ecological principles and demands skills in managing complexity (Jose and Dollinger 2019). This agroforestry system that combines trees and livestock with forage to form a carefully designed system has gained popularity in recent years as an environment-friendly alternative land use system that is economically viable (Jose et al. 2019). The wild expression of this system is the savannah, which is a mid-successional system of grasslands interspersed with trees and shrubs (Freeman and Jose 2009). There has been a tremendous growth in the number of publications on silvopasture in the recent past. Most studies have shown an overall increase in system productivity, including greater productivity of animals. However, comprehensive reviews and synthesis have been rare. Recently, Jose and Dollinger (2019) have published a comprehensive review dealing with four important areas, namely, forage production and quality, livestock performance, environmental benefits and challenges in designing and developing silvopasture in a special Agroforestry Systems of agroforestry systems (Vol 93, Issue 1, February 2019-Silvopasture: A Sustainable Livestock Production). This review has summarized the contents of all 29 articles published in the issue under the above-mentioned four heads.

Retaining and managing trees in pastures improve their productivity and sustainability, especially in seasonally dry climates, through increased nutrient cycling and improvement of soil structure, the provision of dry season cattle fodder and the provision of shade for livestock, which may reduce heat stress and increase feed intake (Amundson et al. 1995; Humphreys 1994; Young 1997). In semi-arid pastoral ecosystems of Latin America, trees have improved soil conditions and herbaceous productivity (Belsky 1994; Rhoades 1997).

The silvopastoral systems (SPS) are found in different tropical and subtropical regions of Latin America and several areas of Africa and Asia (Le Houerou 1987; Kamwenda 2002; Kunst et al. 2016; Soni et al. 2016). In Latin America, farmers practise a wide variety of SPS including small-scale fodder banks for cut-and-carry, intensive silvopastoral systems (ISPS) in Mexico and Colombia and integrated crop-livestock-forestry systems in Brazil (Nunes et al. 2010; Murgueitio et al. 2016; Peri et al. 2016a, b; Somarriba et al. 2018). There are several types of SPS in terms of the different arrangements of grass, shrubs and trees, as well as specific cropping management options. The main silvopastoral practices include (1) pastures between tree alleys, live fences and fodder banks; (2) dispersed trees in pastures—a type of silvopastoral system that has only few trees not exceeding 10–15% of the total area, with the benefits of providing timber, shade and fodder—(3) intensive silvopastoral systems, a type of SPS which involves planting high densities of trees and shrubs in pastures, with improved tropical grasses and trees species or palms (Calle et al. 2012); and (4) timber plantations with livestock grazing areas (Murgueitio et al. 2015; Chará et al. 2017). The use of exclosures has gained widespread acceptance as a means to restore degraded rangeland ecosystems in many of the world's semi-arid rangelands (Verdoodt et al. 2009). The on-site benefits of silvopastoral practices to land users may include additional production from the tree component, such as fruit, fuelwood, fodder or timber; maintaining or improving pasture productivity by increasing nutrient recycling; and diversification of production (Dagang and Nair 2003).

Some examples of silvopastures in different regions of the world have been summarized as follows:

6.7.1 Silvopastoral Systems in North America

Though grazing is old phenomenon in North America, the modern silvopasture management is based on our thinking in both special and temporal domains and demands skills in managing rather than reducing complexity. Management is based on ecological principles, and recently, some interesting information has been generated by some workers. Pang et al. (2019a) tested the effect of moderate (45% sunlight) and dense shade (20% sunlight) on forage yields of 43 species. Their results show that the annual forage yields were higher under moderate shade for all species than under full sun and even higher under dense shade for 31 of them. It was noticed that C_3 grasses were more resilient to shade than C_4 grasses. It was concluded that most grass and legume forages could perform equally well in agroforestry (in partial shade) compared to open pasture systems as long as the root competition with other species is minimal. It was observed that most grass and legume forages would have quality equivalent or even greater crude protein content when grown in silvopasture compared to open pasture (Pang et al. 2019b).

Orefice et al. (2019) evaluated forage production and quality and financial outcomes when an early successional hardwood forest in the USA was converted to silvopasture, open pasture and thinned forest systems. The results showed that the production of forage biomass during second year was similar to the open pasture and the presence of trees increased the nutritive value of the forage without decreasing its digestibility. The financial indicators showed that the silvopasture outperformed open pasture in terms of internal rate of return and net present value. Ford et al. (2019) revealed that the forage productivity was the highest in the open pasture system in Central Minnesota and the lowest in the woodlands. However, when drought conditions prevailed, silvopastoral systems outperformed in terms of forage production. In a comparative study in the Appalachia, Fannon et al. (2019) reported that the pre-graze forage biomass was always higher in the open pasture than in the honey locust (*Gleditsia triacanthos*) or black walnut (*Juglans nigra*) silvopastoral systems; however, the summer productivity was higher in honey locust than walnut system.

Understorey forages present great seasonal and spatial variability and always are not of good quality for cattle grazing. Therefore, for rapid quantification of understorey shrubs such as *Rubus* sp. and *Ulex gallii* as browse in *Pinus radiata* stands, Mendarte et al. (2019) have developed and tested a methodology based on visible and near-infrared spectroscopy (VIS-NIRS), which proved to be very accurate and rapid in predicting the nutritive quality and could, therefore, help to make rapid management decisions in cattle grazing management.

6.7.2 Silvopastoral Systems in Latin/South America

Silvopastoral practices, which combine trees with pasture, offer an alternative to prevalent cattle production systems in Latin America. Caballé et al. (2016) summarized the results of research conducted over the past 15 years and provided management guidelines for the development of silvopastoral systems based on ponderosa pine (*Pinus ponderosa*) plantations established on natural grasslands in north-western Patagonia, Argentina, aiming to generate knowledge for improving environmental and production efficiency of grazing lands in that region. Ecological interactions among the different life forms which make up a silvopastoral system (grasses, trees and animals) were studied to determine what management system would optimize environmental resource sharing. The results suggest that applying silvicultural practices leading to a tree canopy cover level equal to or below 50% is compatible with proper production of natural grassland species, particularly the palatable *Festuca pallescens*. Grass steppes and grass-shrub steppes were dominated by perennial C_3 tussock grasses such as *Festuca pallescens* and *Pappostipa speciosa*, and the spaces among tussocks were dominated by exotic herbs such as *Taraxacum officinale*, native graminoids such as *Juncus balticus* and *Carex gayana* and other C_3 grasses, especially the exotic *Poa pratensis*. The major shrub components were the native *Nassauvia* sp. and *Berberis* sp. Prairies are dominated by the same species found among tussocks described above, plus *Phleum pratense* and *Holcus lanatus*, and the introduced legume *Trifolium repens*. It was concluded that animal rearing should include rotation between different areas in this type of system, where partial shade may limit grass regrowth compared to open grasslands. However, microclimatic benefits of the trees on the animals may be particularly significant and deserve specific future research. The available information indicated that the silvopastoral systems constitute a biologically and environmentally sustainable activity in the fragile ecosystem of semi-arid Patagonia.

Live fences consist of on-line plantings of fast-growing trees and/or shrubs in order to fence off crops, pastures. Near Guapiles in the Caribbean lowlands of Costa Rica, *Gliricidia sepium*, an N-fixing tree, is often planted as a living fence. This is an important firewood species and a good soil improver and has excellent qualities for fodder production and thus is often planted as a living fence. The trees are intentionally chosen to serve their function as a fence and at the same time to improve soils, control erosion and serve as fodder, often in a cut-and-carry system (Montagnini et al. 2013). Barton et al. (2016) have used a Bayesian belief network (BBN) to assess preferred combinations of trees in live fences and on pastures in silvopastoral systems from Rivas, Nicaragua, based on local farmer on knowledge, costs and benefits, farmers' expressed needs and aspirations and scientific knowledge ecosystem services and benefits. These workers concluded that Bayesian belief networks is a promising modelling technique for multi-criteria decisions in farm climate change adaptation processes, whereas agroforestry interventions could be applied to specific contexts and farmer preferences.

The 'forage bank' or 'fodder bank' is generally composed of tree species with highly nutritious foliage for cut-and-carry systems. The trees are planted very densely to encourage foliage production. They are pruned periodically (often weekly), ground, occasionally mixed with cut grasses and then fed to cattle. Examples of tree species that can sustain high fodder productivity in this condition include *Trichanthera gigantea*, *Morus* spp., *Erythrina edulis*, *E. berteroana*, *E. fusca* and *Boehmeria nivea*, which are used with success in Colombia and in Costa Rica (Amézquita et al. 2008). In seasonally dry ecosystems with alkaline soils, *Leucaena leucocephala* and *Brosimum alicastrum* have been found to be promising tree species, whereas in more humid regions with acid soils, the wild sunflower *Tithonia diversifolia* has been proven successful (Murgueitio et al. 2011).

Some case studies are available for Latin America which are described in brief in the following sections:

Colombia Case Studies: Silvopastoral Systems and Carbon Sequestration and Regeneration

In Colombia, several initiatives including projects using SPS approaches to ecosystem management and mainstreaming biodiversity into sustainable cattle ranching have been undertaken. The systems include live fences, scattered trees in pastures, managed plant succession, fodder tree banks and iSPSs (Murgueitio et al. 2011). The implementation of SPSs has contributed to the reduction of deforestation, the use of fire and pesticides and improvement in forage and animal productivity, biodiversity and carbon captures in the participating farms (Murgueitio et al. 2011, 2015).

Multistrata silvopastoral systems

Latin American pastures usually include trees that may be important in sustaining productivity and conserving resources and biodiversity (Cajas-Girón and Sinclair 2001). In the Caribbean region of Colombia, 80–100% of the grasslands are impacted by soil erosion, soil compaction and low soil nutrient availability for livestock systems (Martínez et al. 2014). In the tropical drylands of Colombia, the soils are severely degraded and depleted of plant nutrients due to traditional systems of livestock production (Martínez et al. 2014). Several workers have suggested that multistrata silvopastoral systems can be successfully implemented to improve livestock production and the various soil quality parameters and biodiversity (Murgueitio et al. 2011; Sierra and Nygren 2006; Mcadam et al. 2007; Barros et al. 2003).

A participatory survey of trees in seasonally dry pastures of 54 farms in the Caribbean region of Colombia was undertaken, and data were analysed by cluster and correlation analyses, which showed a multistrata configuration (Cajas-Girón and Sinclair 2001). The findings of this study indicated that the multistrata silvopastoral system was characterized by different species in the different strata. For example, some large stature trees like *Tabebuia rosea*, *Albizia caribaea* and *Sterculia apetala* provided shade and produced timber, whereas the fodder trees (*Albizia saman*, *Guazuma ulmifolia* and *Cassia grandis*) were those of medium size that produced fruits or pods. Other species like *Crescentia cujete* and *Gliricidia sepium* were managed as shrubs producing green leaf fodder and commonly used as living fence posts. Trees were present on between 26 and 69% of the pastures on each farm, at densities varying from less than 3 to more than 50 trees ha $^{-1}$. According to these workers, there is scope to develop silvopastoral systems with woody species familiar to farmers, but it is critical to determine how important different vegetation strata are for sustainability of cattle production (Cajas-Girón and Sinclair 2001).

Martínez et al. (2014) evaluated the effects of 13-year-old multistrata silvopastoral systems on soil quality parameters in degraded soils of the Sinu River Valley, Colombia. These workers showed that the trees in the silvopastoral systems maintained soil pH values and nutrient availability (phosphorus, potassium and calcium) with respect to the pastures with only grasses. The effects were significantly controlled by the types of plant species, particularly *Guazuma ulmifolia* and *Cassia grandis*.

Mainstreaming sustainable cattle ranching in Colombia

In Colombia, the project 'Mainstreaming Biodiversity into Sustainable Cattle Ranching', along with other initiatives, has promoted the establishment of SPS in 5 regions of the country covering more than 2500 farms. The systems include live fences, scattered trees in pastures, fodder banks and intensive silvopastoral systems with *Leucaena leucocephala* and *Tithonia diversifolia* (Murgueitio et al. 2015). In an ISPS with *T. diversifolia* in the Amazon region of Colombia, Rivera et al. (2015) found an increment of 44% in total fodder biomass and 58% in milk production per ha as a result of a higher carrying capacity and individual milk yield when compared to treeless *Urochloa-Brachiaria* pastures. Milk quality was also improved as the production of protein, fat and total solids was 29, 33 and 36% higher, respectively, in the ISPS.

Case Study from the Brazilian Amazon: Inga-Mahogany-Pasture System

In the Brazilian Amazon, pastures have been established by felling primary forest, burning the forest biomass to release the nutrients it contains and planting pasture with Brachiaria spp. Once established, poor management of both livestock and pastures leads to pasture degradation within 7 to 10 years and colonization by the poorly palatable forage. Burning of the pasture leads to the direct loss of nutrients,

Table 6.13 Aboveground biomass and nitrogen stocks in 9-year-old mahogany-pasture system established on degraded pasture land near Manaus, Brazil

Species	Biomass (Mg ha $^{-2}$)	N (kg ha^{-2})
Schizolobium amazonicum (parica')	5.86	23.3
Swietenia macrophylla (mahogany)	5.23	16.4
Brachiaria humidicola/brizantha	4.19	46.1
Desmodium ovalifolium	4.49	67.3
Invasives[a]	2.25	35.8
Gliricidia sepium (live fence)	10.48	73.13
Total	32.5	262.03

[a]Predominantly *Rolandra fruticosa* and *Borreria verticillata*

the loss of nutrients in the residual ash via surface run-off and leaching and loss of soil biodiversity (Fernandes et al. 1997).

An alternative pathway to natural regeneration on degraded pastures in the Brazilian Amazon is the establishment and management of biologically diverse, integrated tree-, crop- and livestock-based systems based on local knowledge of native and migrant farmer systems found in the region (Fernandes et al. 2006). Multispecies agroforests have been identified as promising alternatives for rehabilitation of degraded pasturelands (Fernandes and Matos 1995; Parrotta et al. 1997). According to Fernandes et al. (2006), the Inga (*Inga edulis*)-mahogany (*Swietenia macrophylla*)-pasture system has been found as a promising approach to reintroduce mahogany to deforested and degraded lands in the Amazon for improving biological productivity as well as economic value. *Inga edulis* also occurs as a component in traditional Amazonian agroforestry systems (Pennington and Fernandes 1998). Tapia-Coral et al. (2005) have reported on the development of a substantial and persistent litter layer in Inga-mahogany systems. Nine years after its establishment, the mahogany-pasture system, aboveground biomass and nitrogen stocks are given in Table 6.13.

Mahogany can be sustainably produced by smallholder farmers in association with food crops and pasture species using suitable integrated nutrient management and integrated pest management strategies for the Amazon (Fernandes et al. 2006). Mahogany-pasture system can be applied to supply two of the major commodities (mahogany and beef) via intensively managed systems established on already deforested or degraded pasturelands. Given that these systems also sequester carbon over long rotations, farmers could be provided with payments for carbon sequestration to offset the installation and maintenance costs of the system in the early years.

Case Study from Mexico: Participative Approach for Implementation of Intensive SPS

The tropical regions of Mexico account for 50% of national livestock production. Cattle, sheep and goats are generally produced in extensive systems; the strategy adopted is to expand the iSPS technology based on a participatory approach in which producers, technicians and researchers from national and international organizations jointly participate. The silvopastoral systems include trees, shrubs and pastures. SPS using *Leucaena* as the main shrub forage is growing fast in Mexico (Mauricio et al. 2019). Therefore, several research projects focused on including forage yield and quality of *L. leucocephala* and *Guazuma ulmifolia* as a pure or mixed fodder bank planted in the Yucatan Peninsula, Mexico (Casanova-Lugo et al. 2014). This study by Casanova-Lugo et al. (2014) showed that the mixed fodder bank accumulated more forage yield during the experimental period (10.2 Mg DM ha^{-1} $year^{-1}$) than *G. ulmifolia* alone (9.0 Mg DM ha^{-1} $year^{-1}$) or *L. leucocephala* alone (6.9 Mg DM ha^{-1} $year^{-1}$). The mixed fodder banks of *L. leucocephala* and *G. ulmifolia* were found to be a promising strategy for improving productivity and forage quality as compared to that of the pure fodder banks in Yucatan, Mexico.

6.7.3 Silvopastoral Systems: Some Recent Reports

For comprehensive account of different silvopastoral systems in different regions of southern South America, see Peri et al. (2016a, b); they have compiled studies on silvopastoral systems in different regions (e.g. Misiones and Corrientes, Delta region, western Chaco region in Argentina; north-western Patagonia; temperate, arid and semi-arid zones of Chile; Aysen and Magallanes regions of Chilean Patagonia; and cold zone of Brazil) of southern South America. The main hypothesis of this publication is that farmers have integrated tree and pasture/grassland species in their land use systems to reach higher production per unit of land area, risk avoidance, product diversification and sustainability. These production systems also impact positively in main ecosystem processes. Management of these productive systems and policy and socio-economic aspects provide great opportunities and challenges for farmers and policymakers in that region.

Recently, Jose and Dollinger (2019) reported silvopasture as the sustainable livestock production system and described forage production and quality, livestock performance and environmental benefits and challenges in designing and developing silvopasture in some selected sites. Pezzopane et al. (2019) studied the effect of light restriction on forage productivity in integrated corn-livestock and grass-livestock systems with and without trees in Brazil. They noticed that Piata grass (*Phleum pratense*) yield increased with the distance from the *Eucalyptus* tree line because of decreasing shade but were still greater in the system with trees than in the one without trees. The nutritive value of both forages benefited from moderate shade and improved in the systems with trees and was optimum at a distance of 7.5 m from the tree lines and was higher as compared to the same systems at 1.5 m or 11.5 m or to the system without trees. Differing from the traditional silvopastoral systems, Clavijo et al. (2019) explored the potential benefits of sowing perennial grasses in the understorey of commercial poplar plantations of the Parana River delta in Argentina. They observed that the forage production difference was minimal in summer but increased in sown plots (with grasses) throughout fall and peaked in the winter, and the cattle carrying capacity of the sown poplar stands increased to 0.2 cows per ha in autumn and further by ten times in winter.

Lopez-Santiago et al. (2019) compared the carbon storage of *Leucaena leucocephala* and *Panicum maximum* silvopasture system to those of a deciduous tropical forest and a grass monoculture in Mexico. They recorded higher above-ground biomass at the forest and the silvopasture sites as compared to the prairie, and the greater root biomass and soil organic carbon at all depths were estimated at silvopasture site as compared to other two sites. Aryal et al. (2019) also reported a greater carbon storage potential for the silvopastoral system compared to the open pasture. At global level also, the carbon storage is lowest for the grass monoculture and highest for the silvopastoral system (Jose and Dollinger 2019).

Ascencio-Rojas et al. (2019) and Melesse et al. (2019) characterized the nutrients and cow in vivo and also in vitro digestibility and rumen degradability of forages such as *Diphysa robinioides*, *Gliricidia sepium*, *Erythrina Americana*, *Bursera simaruba*, *Bambusa vulgaris*, *Sesbania sesban*, *Moringa stenopetala*, *M. oleifera*, *Millettia ferruginea*, *Acacia abysinica*, *A. nilotica*, *Leucaena leucocephala*, *Azadirachta indica*, *Cajanus cajan*, *Chamaecytisus palmensis* and *Zanthoxylum riedelianum*. Their results revealed that the dry matter and chemical composition varied with trees and seasons. Legume fodders had a higher effective degradability and crude protein contents as compared to others. The leaves of *Moringa stenopetala*, *M. oleifera*, *Millettia ferruginea*, *Acacia abyssinica* and *L. leucocephala* can be used as alternative protein sources for supplementing low-quality tropical forages. Leaves of *Sesbania sesban* and *L. leucocephala* can be used as alternative source of calcium and magnesium while those of *M. oleifera* and *Millettia ferruginea* as source of phosphorus. Leaves of *Acacia nilotica*, *Prosopis juliflora* and *Cajanus cajan* and pods of *Millettia ferruginea* were identified as potential candidates for mitigating CH_4 production. Thus, it could be concluded that these plant resources along with grasses or agro-industrial products could be an interesting area of research to concurrently reduce ruminal methane formation while enhancing the ruminant's supply with protein sources.

Pinheiro and Nair (2018) compiled studies on silvopastoral system (SPS) consisting of indigenous trees and shrubs in a traditional land use system in the Caatinga, a unique dryland ecosystem of Brazil. There are opportunities to improve the low carrying capacity of the Caatinga by using thinning, coppicing and enrichment planting with desirable tree and understory species. According to these workers, some of the promising interventions include establishment of fodder banks, promotion of non-conventional feed sources such as cactus and introduction of grazing animals to orchards and plantations. There is need of initiating new studies on Caatinga SPS, focusing on the role and potential of various native species and the ecosystem services (Pinheiro and Nair 2018).

6.7.4 Silvopastoral Systems in Africa

Throughout the developing tropics in Africa, much destruction of forests and arable land results from the poor management of grazing animals like cattle, goats, sheep, donkeys and camels. Traditional systems, particularly open grazing, result in the continuing loss of the carrying capacity of the land through severe land degradation, soil compaction and desertification. After working with farming families since 1989 throughout the developing world and coming to understand farmers' needs and constraints as they pertain to livestock, Trees for the Future Organization (TREES) has developed a new system to make livestock production more environmentally and economically sustainable. A major challenge to reducing overgrazing is cultural. In most countries in Africa, there are clear divisions between farmers and herders. Nomads often can't stand farmers, and farmers tend to despise herders. This mashing of lifestyles often escalates into varying levels of conflict often seen in many examples across sub-Saharan Africa. Although alternatives to open grazing, such as rotational grazing, support both animal and pasture health, these methods are often not practical for the poorest of the poor due to investment and equipment requirements. An alternative for animal farmers in the tropics is to produce forages of higher quality in an intensive way and to bring the food to the animals instead of sending the animals to find the food, i.e. cut-and-carry system which represents a smart, blended management approach that is healthier for the animals, more profitable for the farmers and better for our planet. In order to shift millions of smallholder farmers to cut-and-carry systems and reduce the stress on the global environment, these millions of farmers will need to grow fodder banks to have enough forage to feed their livestock. The Forest Garden Approach following which guides farmers in designing and planting fodder tree-rich agroforestry systems that feed growing livestock herds without further degrading soils (trees.org/app/uploads/2016/10/trees-for-livestock-pdf). These systems cause smallholder meat and dairy producers who rely on expensive, commercial animal feed to quickly experience a dramatic reduction in their costs. Animal feed sold by dairy companies and other input providers contain a good balance of fibre and minerals such as calcium, phosphorous, potassium, sulphur, zinc and chlorine, in which fodder from appropriate trees can easily replace. By simply replacing commercial feed with homegrown fodder, farmers realize an immediate savings which can easily double net revenue.

Methodologies are available for the production and marketing of leaf meal from fodder shrub green and nutritive fodder (Franzel et al. 2001). *Calliandra calothyrsus*, *Leucaena trichandra*, *Sesbania sesban*, *S. grandiflora* and *Morus alba*, bearing leaves, with high protein contents, are wildly popular in highland (>1500 m above sea level); *Leucaena leucocephala*, *L. pallida*, *L. diversifolia*, *Morus alba*, *Sesbania grandiflora* and *Senna siamea* are popular in mid- to low-land (< 1500 m above mean sea level) communities of Kenya and Tanzania. These species are also grown as hedgerow crops in many tropical regions of Africa. Other fodder bank popular species of tropical Africa include *Gliricidia sepium*, *Chamaecytisus palmensis* (tagasaste), *Cajanus cajan*, *Pennisetum clandestinum* (kikuyu grass), *P. purpureum* (napier/elephant grass) and *Desmodium intortum*.

Cardenas et al. (2019) evaluated the ecological structure and carbon storage of traditional silvopastoral systems in Nicaragua. They found that the shrub land and secondary forest had higher species diversity and richness than the degraded pasture, the farmed secondary forest and the low and high tree density pastures. They recorded highest carbon storage in the farmed forest and in the high tree density pastures followed by shrub land and the low tree density pastures.

Some important site-specific systems are described below:

6.7.4.1 *Ngitili* Agrosilvopastoral Systems

Environmental degradation resulting from extensive grazing and indiscriminate exploitation of rangeland forestry resources is a severe problem for the agropastoralist of Shinyanga, a northeastern region of Tanzania. Threats to livelihoods and the environment in this region include mostly shortage of dry season fodder, deforestation, woodfuel scarcity, food insecurity and severe soil erosion. However, a traditional management system locally termed *ngitili* (dry season fodder reserves) among the Wasukuma agropastoralists of Shinyanga has proven to be instrumental in range management and forest restoration. The system at the same time diminishes dry season fodder shortages, prevents environmental degradation such as soil erosion and helps conserve biodiversity. Under the HASHI programme, 350,000 to 500,000 ha of woodland were restored in the period from 1986 to 2001. *Ngitili* are farmer-led initiatives which evolved from traditional strategies for grazing and food security. The system involves retaining an area of standing vegetation (grasses, trees, shrubs and forbs) from the onset to the end of the rainy season to increase fodder production and supply of tree products (Kamwenda 2002). The ngitili area remains closed to livestock at the beginning of the wet season and is opened up for grazing at the peak of dry season. A survey was conducted based on World Agroforestry Centre (ICRAF) methodology in the Meatu District of Shinyanga region, Tanzania, to identify the components, structure, management and technological specifications of the system (Kamwenda 2002).

According to Kamwenda (2002), *ngitili* have two major components: vegetation and animals. The animal component encompasses mostly goats, cattle, sheep and donkeys. The interaction of livestock with vegetation has a significant role in the management and sustainability of the system. Two distinct vegetation strata are identifiable, an upper stratum dominated by *Acacia tortilis*, *A. nilotica*, *A. polyacantha* and *A. seyal* and a lower stratum of grasses, herbs and forbs. This study reported 17 commonly grazed fodder grasses, 25 commonly browsed herbs and forbs and 25 browsed tree species used in *ngitili* as given in Table 6.14. The system was found sustainable as it fulfilled the required levels of production of dry season fodder supplies and food for security and reducing the risk of severe soil erosion and deforestation. Moreover, *ngitili* as a traditional practice has a great potential to improve soil ecology and biodiversity of the sites, where different functional groups of plants grow together. Trees stabilize the soils because they are usually rooted deeply, and they enrich the surface soil with their litter input from aboveground and belowground parts of the plans. The extensive ground cover of the plants reduces run-off, helps prevent soil erosion and facilitates water infiltration, percolation and storage in soil.

In the northern highlands of Ethiopia, establishment of enclosures to restore degraded communal grazing lands has been practised for the past three decades (Mekuria and Aynekulu 2013). These workers selected replicated (n = 3) 5-, 10-,

Table 6.14 Common tree species found in *ngitili* and their environmental and fodder roles in Meatu District of Shinyanga region, Tanzania (based on Kamwenda 2002)

Species	Environmental role	Parts foraged
Acacia albida	Nitrogen fixation, shade, soil conservation, dune fixation, soil improvement	Pods
Acacia mellifera	Nitrogen fixation, soil conservation, dune fixation	Pods
Acacia nilotica	Soil improvement, wind break, nitrogen fixation, soil conservation	Leaves
Acacia polyacantha	Nitrogen fixation, ornamental, soil improvement	Leaves, pods, seeds
Acacia saligna	Mulch, shade, soil improvement, nitrogen fixation, soil conservation	
Acacia senegal	Nitrogen fixation, shade, soil conservation, soil improvement	Leaves
Acacia tortilis	Nitrogen fixation, shade, soil conservation, soil improvement, windbreak	Leaves, pods, seeds
Albizia gummifera	Nitrogen fixation, shade, mulch, soil conservation, dune fixation, soil improvement	Leaves, fruits
Dalbergia melanoxylon	Mulch, nitrogen fixation	Leaves
Erythrina abyssinica	Ornamental, mulch, nitrogen fixation	Leaves
Trema orientalis	Mulch, shade, soil conservation, ornamental, dune fixation	Leaves, fruits, pods
Ziziphus mauritiana	Soil conservation, windbreak	Leaves

15- and 20-year-old exclosures and paired each exclosure with samples from adjacent communal grazing lands. All exclosures showed higher total soil nitrogen (N), available phosphorus (P) and cation exchange capacity than the communal grazing lands. Rehabilitation of degraded rangelands has also been undertaken through establishment of exclosures in Kenya (Verdoodt et al. 2009; Wilkerson et al. 2013; Mureithi et al. 2014) and South Africa (Siebert et al. 2010). Verdoodt et al. (2009) assessed the vegetation and soil rehabilitation in a 23-year chronosequence of two different enclosure management types in the severely degraded, semi-arid Njemps Flats plain of the Lake Baringo Basin in Kenya. There were significant improvements in topsoil bulk density, organic C and total N stocks and microbial biomass C and N stocks of the communal enclosures as compared to the open rangeland.

Mureithi et al. (2014) showed a significant increase of absolute stocks of carbon, nitrogen and microbial biomass in reseeded communal enclosures using soil embankments as water-harvesting structures compared to the degraded open rangeland in the Njemps Flats in Baringo County of Kenya. This study indicates the potential for the restoration of soil quality through range rehabilitation. Over-sowing with indigenous legume fodder species could improve total nitrogen content in the soil and nutritional value of the pastures as well (Mureithi et al. 2014). The results of this study showed that enclosures are effective in restoring the nutrient status and quality of degraded soils.

Restoring degraded ecosystems through the establishment of exclosures has been successful in the Ethiopian highlands (Mekuria and Aynekulu 2013; Mekuria et al. 2017). Mekuria et al. (2018) studied changes in vegetation composition, aboveground biomass and soil properties after establishing an exclosure on degraded communal grazing land in Aba-Gerima watershed, north-western Ethiopia. In the exclosure, they reported 46 plant species representing 32 families and found 18 plant species representing 13 families in the adjacent communal grazing lands. Most of the identified woody species are economically important. There were significant differences between the exclosure and adjacent grazing land in woody species richness, diversity and evenness. The enclosure displayed higher woody species density, basal area and aboveground woody biomass and greater improvement in soil properties compared to the adjacent grazing land (Mekuria et al. 2018).

6.7.4.2 Parkland Systems

Parklands constitute the predominant forage systems in semi-arid West Africa. In the Sahelian zone, crops grown under discontinued cover of scattered trees dominate 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 monospecific (e.g. *Faidherbia albida* and *Borassus aethiopum* based), but others have dominant tree species mixed with a range of tree and shrub species (Boyala et al. 2014). Agroforestry in Burkina Faso with *Borassus akeassii* and *Faidherbia albida* can be seen in Fig. 6.5. In some cases, the original species such as *Prosopis africana*, *Vitellaria paradoxa*, *F. albida*, *Parkia biglobosa*, etc. are retained, while in others cash plantations such as oil palm (*Elaeis guineensis*) are introduced while in others (e.g. *Adansonia digitata*) even fruits and leaves are collected systematically,

Fig. 6.5 Agroforestry in Burkina Faso with *Borassus akeassii* and *Faidherbia albida*. Source: https://upload.wikimedia.org/wikipedia/commons/e/e8/Faidherbia_albida.JPG; attribution Marco Schmidt [1] [CC BY-SA 2.5 (https://creativecommons.org/licenses/by-sa/2.5)]

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 parkland is the most common and improved agroforestry in these countries and combines 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 aegyptiaca*, *F. albida*, *Pterocarpus erinaceus*); wood for fuel, construction, household and farm implements (e.g. *B. aegyptiaca*, *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 to 25–75% of annual household revenue in Mali (Faye et al. 2010), with some having international market.

Information on many silvopastures of Africa is also covered under the section introduction of trees on pastures in this chapter and most of the savannahs. Moreover, many chapters from African regions have been included in this publication itself. The repetition has been avoided.

6.7.5 Silvopastures of Asia and the Pacific Regions

These regions are often described as the cradle of agroforestry in recognition of their long history of the practice of an array of systems under diverse agroecological conditions. Multitudes of agroforestry systems are found in these regions starting from isolated and boundary trees on farm land to complex home gardens. These systems have evolved in the region over long periods which reflect the accrued wisdom and adaptation strategies of millions of smallholder farmers to meet their basic needs of food, fuelwood, fodder, plant-derived medicines and cash income in the wake of increasing demographic pressure and decreasing land availability. Livestock-based systems are most prevalent in all regions starting from arid ecology of Thar Desert (spread in Indian subcontinent) to humid climate of coastal India and the Pacific countries. In these humid regions, animals graze under plantations, mainly coconut. There are many plantations which are preferred as grazing ground as shown in Table 6.15. It gives an indication of preferred animal options that are appropriate for individual tree crops. Small ruminants appear to be favoured in most cases.

There are many benefits of crop-animal-soil interactions which result from the synergistic interactions of the system components. The common interaction results in tangible benefits which include (Devendra 2014) beneficial effects of shade and available feeds on livestock; draught animal power for land preparation and crop dung and urine for soil fertility and crop growth; crop residues and agro-industrial by-products from trees in situ; effects of native vegetation on the cost of weed control, crop management and crop growth; and type of animal production systems

Table 6.15 Potentially important perennial crops (mainly plantations) and their locations for use in integrated livestock-based systems in the tropics

Plantation	Location	Preferred animals
Coconut	South India, Indonesia, Philippines, Thailand, Sri Lanka, South China	LR and SR
Cashew	Vietnam, South India	SR
Cocoa	Malaysia, Papua New Guinea, Cote de Ivorie, Indonesia, Nigeria	SR
Oil palm	China, Indonesia, Malaysia, Papua New Guinea, Thailand, Columbia, Nicaragua	LR and SR
Rubber	Schema, Indonesia, Philippines, Malaysia, Thailand, Brazil	SR
Teak	Lao PDR, Myanmar	LR
Citrus	India, Philippines, Thailand, Vietnam	SR
Fruit trees (mango, plantain, etc.)	India, Philippines, Thailand, Costa Rica	SR and LR

LR large ruminants (buffaloes and cattle), *SR* small ruminants (goats and sheep)
Source: Devendra (2014)

(extensive systems combined with arable cropping and systems integrated with tree cropping) leading to increased income and environmental integrity.

Tree species such as *Salvadora oleoides*, *S. persica*, *Capparis decidua*, *Acacia nilotica*, *A. leucophloea*, *Prosopis cineraria* and now *Prosopis juliflora* are most frequent trees on common community grazing lands in India. In coastal areas, coconut is the most common tree on pasturelands of arid and semi-arid regions. Cattle raising usually involves grazing on these pastures. An organized form of this natural vegetation as silvopasture assures 10 Mg ha^{-1} year^{-1} biomass production (as against 1 Mg ha^{-1} year^{-1}from natural stands) at 10-year rotation in dry zones besides assuring soil conservation, healthy environment and employment generation (Pathak et al. 1995). The role played by *Prosopis cineraria* in dry ecologies of India is similar to *Faidherbia albida* in Africa. It is now well-established in sustaining the yield of both crops and forages and also ameliorating the soil. While explaining the nature of grassland dynamics and their management, Dagar and Pathak (2005) gave a comprehensive information when trees play crucial role in the management of grazing lands. Based on long-term studies, Rai (2012) reported the role played by many multipurpose trees such as *Ailanthus excelsa*, *Acacia tortilis*, *Hardwickia binata* and *Leucaena leucocephala* in silvopastoral systems for livestock production in arid and semi-arid regions.

As stated earlier, grazing lands/range lands are not a defined landscape, but these are found in varied edaphic and climatic situations. In present context when we are discussing the concern regarding their improvement in terms of productivity and soil health, we may discuss in brief some specific situations where grazing is prominent. For example, most of the watersheds of the rivers, especially ravine lands; community lands especially salt-affected degraded lands; open sand dunes in arid regions; and coconut plantations in coastal areas remain exposed to overgrazing. Some of these cases, with special reference to the approaches being or may be adopted to improve these resources, are discussed here in brief.

6.7.5.1 Silvopastures for Eroded Watersheds

The desertification, land degradation and drought processes have accelerated rapidly in the last century, with an estimated 24 billion Mg of fertile soil lost to erosion in the world's crop lands (FAO 2011). Soil erosion has socio-economic, environmental and technical dimensions. Those who suffer the most are poor farmers and landless labourers, who are least able to adopt conventional measures for its control. A more beneficial alternative in eroded ecologies in both high rainfall and semi-arid 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 may be blended suitably with spices such as clove, cardamom, black pepper and even fruits like pineapple. The sloping lands may be planted with alley crops, mainly fodder and nitrogen-fixing species such as *Gliricidia sepium*, *Leucaena leucocephala*, *Cassia siamea*, *Morus alba*, *Pithecellobium dulce* and *Cajanus cajan*, and fodder grasses as intercrops.

In arid and semi-arid regions all along the rivers and their tributaries, the soil is mostly alluvial and prone to soil erosion, and a net of gullies and deep ravines is formed. The phenomenon is more common along Indian rivers where about 4 million ha fall under ravines. Rehabilitation of ravine lands involves treatment of table and marginal lands (contributing run-off to the gullies) on watershed basis. It requires an integrated approach of using gullies according to land capability classes, soil and water conservation measures and putting land under permanent vegetation cover involving afforestation or agroforestry, horticulture, pasture and energy plantations (Chaturvedi et al. 2014; Dagar 2018a, b). Protection from grazing and afforestation with suitable species is the most effective measure for checking soil erosion and consequently ravine formation.

Woody species, mostly of fodder value found growing in eroded habitats, may find priority in afforestation program (Dagar 2018b). For example, *Acacia nilotica*, *A. eburnea*, *A. leucophloea*, *A. catechu*, *Azadirachta indica*, *Albizia lebbeck*, *Balanites roxburghii*, *Butea monosperma*, *Dalbergia sissoo*, *Dendrocalamus strictus*, *Dichrostachys cineria*, *Eucalyptus* spp., *Feronia limonia*, *Pongamia pinnata*, *Prosopis juliflora* and *Ziziphus mauritiana* have been found to adapt easily in the ravines of Yamuna River 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. As stated in earlier section, after protecting from grazing, many local grasses, which are good fodder and adaptive to the eroded situation and conserve the soil efficiently, must find a place in establishing a viable silvopastoral system in these habitats (Dagar 2018b).

The terrace risers of agricultural fields may be planted with suitable grasses which help in conserving soil and crop productivity. 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 was found to be increased by 23–40% and 10–20%, respectively, when cultivated with grass barriers in addition to 0.6–-1.7 Mg ha^{-1} $year^{-1}$ grass yield (Ghosh 2010). Hedge rows of trees such as *Leucaena* and *Gliricidia* are quite effective in controlling soil erosion when plated 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). Integrated watershed management programs are being implemented in India on a massive scale since 1991, which is most sustainable multipurpose strategy. A review of more than 300 integrated watershed management programs indicated that in majority of them total crop production increased by 50–123% (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 stake holders in generating employment, and about 47% of degraded lands have been treated for rehabilitation (Sharda et al. 2008). In remaining projects, agroforestry may be incorporated as main component particularly on highly degraded areas.

The important measure that can be adopted for reducing the risk of degradation of gullies and marginal lands along the ravines is introduction of trees in cropping lands and perennial grasses on field bunds. Depending on slope and extent of problem and needs, the trees may be planted as alley, boundary plantation or scattered trees in field, but all along, the boundary facing gully/ravine hedges of suitable species such as *Carissa carandas* and *Balanites roxburghii* supported by perennial grasses must be at place. Besides controlling soil erosion by such systems, the overall economic returns have been found better as compared to sole crops in these habitats (Parandiyal et al. 2006). A long-term study (Prajapati et al. 1993) to assess the fuel and fodder production in Yamuna ravines revealed that after 15 years of planting, the fuelwood production was 28.7 Mg ha^{-1} in *Acacia tortilis* and 27 Mg ha^{-1} in *A. nilotica* raised at 3 m × 3 m spacing. The biomass ranged between 7.6 Mg ha^{-1}at ravine top (5 m × 5 m spacing) and 34.4 Mg ha^{-1}at ravine bottom (3 m × 3 m spacing) in *A. nilotica*, while the corresponding yields of *A. tortilis* were 11.5 Mg $ha^{-1}$and 30.2 Mg ha^{-1}, respectively. The mean annual pasture yield ranged from 1.5 Mg ha^{-1} $year^{-1}$at 3 m × 3 m spacing to 1.8 Mg ha^{-1} $year^{-1}$at 5 m × 5 m spacing under *A. nilotica* and 1.8 to 2.1 Mg ha^{-1} $year^{-1}$, respectively, under *A. tortilis* at similar spacing. The top feed production from *A. nilotica* was 3.8 and 5.2 Mg ha^{-1}in respective spacing and 3.8 and 3.1 Mg ha^{-1} in *A. tortilis* at the age of 14 years. In another study, Parandiyal et al. (2006) found that the impact of *A. nilotica*, *Azadirachta indica* and *Albizia lebbeck* trees grown as boundary plantations in associated field crops of castor (*Ricinus communis*) and pigeon pea

(*Cajanus cajan*) raised in two sequences in the marginal lands near ravines, and the yield reduction in the vicinity of trees was compensated well from income of fuelwood produced by trees; rather there was benefit of tree growing and the soil erosion was in control. Under alley cropping system, sorghum was found to be more compatible with *Leucaena* as compared to pigeon pea (Prasad and Singh 1994). In one study, Prajapati et al. (1993) observed that *A. nilotica* and *A. tortilis* when grown at the bottom of ravines could produce biomass of 30.2 to 34.4 Mg ha^{-1}.

Land Class IV may also be put under silvopasture systems. By planting grasses (through seeds or cuttings), good fodder yield is achieved in 2–5 years. Grasses such as *Cenchrus ciliaris*, *C. setigerus*, *Panicum maximum*, *P. antidotale* and *Pennisetum purpurium* could provide 5–7 Mg ha^{-1} year^{-1} dry fodder, equivalent to 18–-20 Mg ha^{-1} green fodder. This practice also reduces run-off and soil loss considerably to the tune of 6–10 Mg ha^{-1} year^{-1}. Dagar and Pathak (2005) while reporting the ecology and management of grazing lands in India advocated that in highly eroded habitats, the first task must be control on grazing followed by introduction of local trees and perennial grasses and legumes. Ravenous catchments when planted with *A. nilotica* + *Dichanthium annulatum* and *D. annulatum* alone generated 5.8 and 2.6% of run-off and 1.26 and 0.62 Mg ha^{-1} of soil loss, respectively, compared to 14.7% of run-off and 3 Mg ha^{-1} of soil loss from agricultural catchments. Production of 4.5 Mg ha^{-1} air-dried grass + firewood 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). Planting of grasses further leads to improvement of soil structure and organic matter in these highly eroded habitats. Silvopastoral systems have been advocated to be most ideal for ravine lands and highly erodible soils (Prajapati et al. 1989; Dagar 1995a; Chaturvedi et al. 2014; Dagar and Gupta 2016; Dagar 2018b). Recently, Dagar and Singh (2018) have compiled global information on greening of ravine lands for environmental and livelihood security. 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 in the vicinity of ravines.

6.7.5.2 Silvopastures for Drylands

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. These areas are also exposed to overgrazing as livestock rearing is the main livelihood resource for the people of this region. The most important measures for sand dune stabilization are covering the area under trees and providing a surface cover of grasses followed by their protection against biotic interference. Besides fixing the sand dunes, it is important to check the movement of loose sand by applying wind breaks and mulch. Locally available brushwoods like *Leptadenia pyrotechnica*, *Calligonum polygonoides* (now rare due to over-exploitation), *Ziziphus nummularia* and *Aerva tomentosa* and grasses like *Cenchrus*

Fig. 6.6 The *khejri* tree (*Prosopis cineraria*) providing shade to sheep, goat and cattle in desert area near Jaisalmer, Rajasthan, India (Photo credit Dr. Mahasingh Poonia)

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.

The desert vegetation is mostly herbaceous or stunted scrub; drought-resistant trees sparsely dot the landscape, especially in the east. On the hills, gum *Arabic acacia* (*Acacia nilotica*) and species of *Euphorbia* may be found. The *khejri* tree (*Prosopis cineraria*) grows throughout the plains (Fig. 6.6), fixes large amounts of nitrogen, maintains soil fertility and provides shade to the animals in summer. The tree is favoured for agroforestry as it fixes large amounts of nitrogen and does not affect growth of plants under the canopy.

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 such as *Cenchrus ciliaris*, *C. setigerus*, *Dichanthium annulatum* and *Panicum antidotale* have been found most successful for sand dune stabilization. These grasses can yield 2.2 to 3.8 Mg ha^{-1} year^{-1} dry fodder with no ill effect on tree growth. Silvopastoral system is most viable, sustainable and profitable system. If need arises, one or two irrigations of saline water up to EC_{iw} 10 dS m^{-1} may be applied during dry period. It will also assure intangible benefits such as amelioration of soil, climate, control of soil erosion, shelter to annual crops in vicinity and protection to wildlife. Agroforestry systems for African continent have been discussed in separate chapters in this volume.

More than 30% area of hot desert is sandy plain. In this landform, very little efforts are required for land preparation for planting of saplings. For planting tree

Fig. 6.7 Sewan grass (*Lasiurus scindicus*) intercropped with acid lime (*Citrus aurantifolia*) in arid regions of Rajasthan. Photo Courtesy: Dr. Moti Lal Soni

saplings, pits of 50 cm × 50 cm × 50 cm are excavated, and a saucer-shaped basin of 1 m diameter around each pit is made so that more rainwater could be harvested for seedling establishment. This type of landform occurs throughout the arid zone in rainfall gradient of 150 mm to 350 mm. The important tree species found in the region include *Prosopis cineraria*, *Acacia senegal*, *Salvadora oleoides*, *Capparis decidua*, *Azadirachta indica*, *Ailanthus excelsa*, *Tecomella undulata* (three forms) and *Balanites roxburghii*. These have good drought tolerance ability and are part of traditional as well as improved agroforestry systems. Grasses such as *Lasiurus sindicus* along with *Citrus aurantifolia* are efficient builder of biomass (Fig. 6.7). In *Hardwickia pinnata* (tree)-*Cenchrus ciliaris* (grass)-based improved 9-year-old silvopastoral system (trees planted in 3 m × 3 m space), the average carrying capacity was 4.1 sheep ha^{-1} $year^{-1}$ against 3.7 for sole pasture and 1.6 for sole tree component. In this system, in addition to grass + tree top (3.1 Mg ha^{-1} $year^{-1}$), a biomass of 260 kg ha^{-1} $year^{-1}$ of fuelwood was also obtained (Tewari et al. 2014).

Diversified production systems appear to be very sustainable for hot arid regions. Trees like *Prosopis cineraria*, *Z. nummularia*, *Z. mauritiana*, *Tecomella undulata*, *H. pinnata*, *Cassia siamea*, *Acacia tortilis*, *A. nilotica* and many others play 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 reputed for its role in improving crop productivity as well as conservation and amelioration of soil. In one 2 years' study with mature trees, Tewari et al. (2014) reported that amount of average soil loss with shelterbelts of *P. juliflora*, *Cassia siamea* and *A. tortilis* was 351.2, 184.2 and 300 kg ha^{-1} in comparison with

Table 6.16 Available macro—and micronutrients under different tree-based agroforestry systems

Tree species	Micronutrients (kg ha^{-1})			Micronutrients (ppm)			
	N	P	K	Zn	Mn	Cu	Fe
Prosopis cineraria	221	11	479	1.44	10.8	0.89	2.8
P. juliflora	231	7	333	0.89	9.3	0.58	3.3
Without tree	199	6	3	0.19	7.0	0.38	3.5

Source: Tewari et al. (2014)

546.8 kg ha^{-1} in agricultural field without trees. They also observed increase in available nutrients in association with trees (Table 6.16) proving that trees improve the soil health in arid ecologies.

Many dry regions also have shallow soil, particularly in the eastern and south-eastern parts of Rajasthan and Kutch area of Gujarat, and are exposed to overgrazing. 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 pinnata*, *Capparis decidua*, *Grewia tenax*, *Ziziphus nummularia*, *Holoptelea integrifolia* and *Dichrostachys nutans*. Some areas in these pockets are extremely rocky and gravelly found scattered, and 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 et al. (2014) have given illustrative 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} year^{-1} fruit, leaf fodder and fuelwood, respectively (Tewari et al. 1999).

One study conceptualized the availability and production of biomass from grasslands under natural pasture, improved pasture, silvopasture and a synthetic multitier canopy system in Bundelkhand region in Central India. The production in natural grazing land was seasonal for only 3 months with less than 1 Mg dry matter ha^{-1} year^{-1}, while a multitier system if properly synthesized could give about 8 Mg ha^{-1} year^{-1}. Based on this hypothesis, silvopastoral systems were developed involving different tree species including *Albizia lebbeck*, *A. amara*, *Dalbergia sissoo* and *Leucaena leucocephala* and grasses and legumes such as *Cenchrus* *ciliaris*, *Dichanthium annulatum*, *Panicum maximum*, *Stylosanthes seabrana*, *S. hamata*, etc. At the end of 6 years, it was possible to harvest biomass of 10 Mg ha^{-1} $year^{-1}$ and 14.6 Mg ha^{-1} $year^{-1}$under a small farmer situation (Pathak and Dagar 2015). This study showed the merit of appropriate management and input decisions that could improve land productivity. The improved land capability also helps higher productivity and livestock carrying capacity.

In Pakistan, about 11 million ha land resources are desert (Thal, Thar, Choliston and Chaki-Kharan) exposed to overgrazing 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 ranging from ECiw 4 to 18 dS m^{-1}. These areas can 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., *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).

Al Muzaini (2003) gave environmental measures including plantation methods to control sand movement in Kuwait where it has caused extensive deterioration of the desert ecosystem. Palms including date palm (*Phoenix dactylifera*) and *Eucalyptus* sp. were 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 fibre and as bioactive derivatives) for sustainable biosaline farming systems in the Middle East. Dagar (2018c) reported several halophytic species of economic importance (including food-, fodder-, oil- and medicine-yielding) for growing in different saline environments including pasture lands. 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 proven to boost maize yields, especially in low-fertility soils (Garrity et al. 2010). Ismail et al. (2019) have given a detailed account of forage production in arid regions of UAE using saline water for irrigation. Many species of *Atriplex*, *Chenopodium*, *Pennisetum* and *Salicorni*a have been tested and found suitable.

6.7.5.3 Silvopastoral Systems on Salt-Affected Grazing Lands

About 1 billion hectares of land are considered salt-affected, and majority of these lands though unproductive are exposed to overgrazing. Sodic soils (pH >8.5, ECe <4 dS m^{-1}, ESP >15) have hard calcic layer in upper 50–120 cm depth, hence difficult for tree plantations. Now, auger-hole technique is available to pierce this layer and plant salt-tolerant tree plantations. Dagar et al. (2001), Singh and Dagar (2005) and Dagar (2014) have identified and reported several suitable tree and grass species for developing successful silvopastoral systems for such soils. *Prosopis juliflora*, *P. alba*, *Acacia nilotica*, *Tamarix articulata* and *Eucalyptus tereticornis* are most successful trees for high pH (~10) soil, and *Leptochloa fusca*, *Brachiaria*

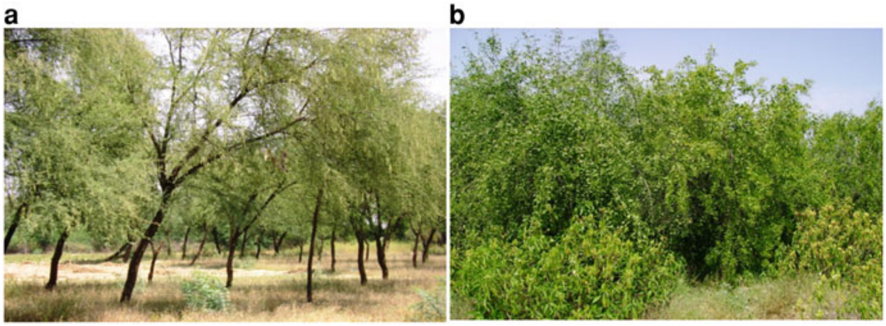

Fig. 6.8 (**a**) A view of *Acacia nilotica* + *Cenchrus ciliaris* silvopastoral system, (**b**) *Salvadora persica* + mixed-grass silvopastoral system on a highly calcareous sandy loam soil irrigated with saline water at Hisar in north-western India (Photo: SR Gupta)

mutica, *Chloris gayana* and *Panicum laevifolium* are the suitable grass species for these soils. *Vetiveria zizanioides*, *B. mutica* and *L. fusca* also tolerate waterlogging. *Prosopis*-*Leptochloa* silvopastoral system has been considered to be most suitable to reclaim these soils. Grewal (1984) developed a silvopastoral model for rainwater conservation and production of fuel and forage from alkali lands. Trees such as *Acacia nilotica*, *Eucalyptus tereticornis* and *Parkinsonia aculeata* were planted on ridges, and kallar grass (*L. fusca*) was established in the trenches between ridges. Besides producing forage and fuelwood, this system could conserve rainwater during monsoon, which in turn increased forage in the interspaces and growth of trees on ridges. Thus, the system was found quite useful in checking run-off and soil loss and conserving moisture. For saline soils, *Casuarina glauca*, *Tamarix articulata*, *Acacia tortilis*, *Salvadora oleoides* and *Parkinsonia aculeata* among trees and *L. fusca*, *B. mutica* and *Atriplex* spp. among forages are considered most suitable species.

In one experiment, conducted on saline black soils (Vertic Ustochrepts) with about 2 to 3% salt in the surface of 30 cm soil which are otherwise predominated by salt-tolerant grasses like *Aeluropus lagopoides*, *Aristida adscensionis*, *Sporobolus marginat*us and *Dactyloctenium aegyptium*, it was found that *Leptochloa fusca*, *Dichanthium annulatum* and *Eragrostis* sp. could produce on an average 3.72, 1.8 and 1.0 Mg ha^{-1} year^{-1} forage, respectively (Dagar 2014), and along *Salvadora persica*, *Prosopis juliflora* and *Azadirachta indica* form ideal silvopastoral system.

The silvopastoral agroforestry systems (Fig. 6.8), characterized by tree species of *Acacia nilotica* and *Salvadora persica* along with native grasses of *Cenchrus ciliaris* and *Panicum miliare*, and agrihorticulture system of *Carissa carandas* with *Hordeum vulgare* were studied by Kumari et al. (2018). In the silvopastoral systems, total carbon stock (Mg ha^{-1}) was 102.81 to 138.23 *Acacia nilotica* + *Cenchrus ciliaris* system and 112.53 to 181.51 *Salvadora persica* + mixed-grass system.

For more details, see Dagar (2014) and Dagar and Minhas (2016) and a separate chapter included in this volume.

6.7.5.4 Pasture Development Under Old Plantations

In India, about 3.7 million ha of land is under miscellaneous tree crops and groves, out of which 1.9 million ha is under coconut alone. Same is the story of many Indo-Pacific regions. Most of ground areas under these plantations lie unutilized and are open to stray animals for grazing, and soil cover is either negligible or covered by wild bushes or unpalatable weeds. These plantations provide ideal site for development of pasture/fodder resource without interfering with the fruit production. The available information on plantation-based systems on grazing lands and vice versa suggests that the carrying capacity under the old coconut plantations ranges from 0.5 to 3.0 animals per hectare and is capable of achieving a growth rate of 135 kg per animals per year (Rika et al. 1981). Fertilizer use efficiency of plantation-based fodder farms is more than open area farming. In high rainfall areas, forage grasses like guinea hamil (*Panicum maximum*), dinanath (*Pennisetum pedicellatum*), hybrid napier (*P. purpureum*) and Guatemala (*Tripsacum laxum*) and legumes like calopo (*Calopogonium mucunoides*), centro (*Centrosema pubescens*), sirato (*Phaseolus atropurpureum*) and stylo (*Stylosanthes guianensis* and *S. hamata*) were successfully grown under the old plantations of coconut. In a specific study, it was found that *Andropogon gayanus*, *Brachiaria mutica*, B. ruziziensis, *Panicum maximum*, *P. antidotale*, *Pennisetum polystachion*, *P. purpurium*, *P. pedicellatum*, *Setaria anceps* and *Tripsicum laxum*, when grown in coconut beds, could yield 18 to 33 Mg ha^{-1} dry forage per annum (Sharma et al. 1991; Dagar 1995b; Dagar and Singh 1999; Dagar 2000). Legumes such as *Calopogonium mucunoides*, *Clitoria ternatea*, *Phaseolus atropurpureus*, *Stylosanthes guianensis*, *S. scabra* and *Leucaena leucocephala* form excellent cover under plantations to check erosion and also provide excellent fodder. Sharma et al. (1991) reported comparative yield performance and water use efficiency of 11 exotic grasses in the humid tropics which were found suitable and successful for these regions.

Efficient production systems are important and silvopastoral systems are not so well developed, in spite of the fact that tree plantations of oil palm are abundant in countries like Indonesia and Malaysia (Davendra 2014). In some regions of the tropical Asia, silvopastoral systems involving trees and animals (e.g. coconuts, oil palm and rubber) and agropastoral systems integrating crops, animals and trees have been reported (Davendra 2014). For example, in Indonesia, Malaysia, Papua New Guinea and Thailand, large, small ruminants (buffaloes and cattle) and small ruminants (goat and sheep) can be integrated in oil palm plantations. There are opportunities for adaptive research, for example, sheep and coconuts in the Philippines and the development of sustainable silvopastoral systems; small ruminants appear to be favoured in most cases because of the fact that ruminants provide the entry point for the development of integrated tree crop-ruminant systems (Davendra 2014). Goats have the ability to digest fibrous feeds and especially coarse roughages efficiently in oil palm plantations (Devendra 2007). The available forage biomass under oil palm can be more fully utilized if mixed grazing is involved, such as goats and cattle.

6.8 Conclusions

With more than 180 million pastoralists worldwide now trying to make a living tending 3.3 billion cattle, sheep and goats, grasslands are under heavy pressure. As a result of overstocking, the grasslands (basically grazing lands) are now further deteriorating in much of the developing world. Most of the rangelands in developing countries are on degraded and problematic lands. The current and future demands of feeds and fodder can be met only if sincere efforts are made at political, scientific and farmers' levels to improve physico-chemical and biological conditions of degraded grazing lands. There is no alternative to improving local fodder production, if we want to cater to the perishable animal product demands of the ever-increasing population. Conversion of degraded grazing lands into scientifically managed fodder farms/silvopastures is essential to effectively meet the year-round fodder demands. Growing of indigenous potential nitrogen-fixing fodder trees on pasture lands can be encouraged under silvopasture programs in social forestry. The species of grasses, shrubs or trees need to be selected according to the soil type, altitude, temperature and precipitation and depending on socio-economic benefits. Studies have been carried out with silvopastoral systems in many Latin American countries and have accumulated important experience in adopting and adapting SPS to local conditions. Intensive silvopastoral systems are a good example of a land use in Latin America that can increase the productivity of grazing lands and enhance the generation of ecosystem goods and services. In Latin America, silvopastoral arrangements have the potential to be established in most of the locations where cattle ranching is practised. There is a need to mainstreaming of silvopastoral systems in rehabilitating degraded grazing lands to simultaneously address environmental sustainability and meet the sustainable production objectives from the land. There is also a need to create awareness among farmers, greater research efforts and sound implementation of government initiatives for sustainable management of grazing lands.

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Potential of Agroforestry for the Rehabilitation of Degraded Ravine Lands

7

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Abstract

Degraded ecosystems face depletion of flora and fauna and loss of productivity due to various abiotic and biotic disturbances resulting in slow recovery during natural succession of vegetation. With an estimated 3.7 Mha of land affected by it, the ravines pose a major problem along several river systems in the alluvial zones in India. The declining per capita land availability over the years has necessitated efforts for arresting further degradation and reclaiming these lands for realizing their production potential. Agroforestry may potentially improve the economic utilization of these lands through simultaneous production of food, fruit, fodder and firewood, carbon sequestration as well as mitigation of the impact of land degradation. Optimum utilization of suitable species of trees, shrubs and grasses is important in ravine rehabilitation efforts. Agroforestry measures have been identified for rehabilitation of ravine lands involving treatment of table and marginal lands contributing runoff to the gullies and for economic utilization of gullied ravines.

Keywords

Degraded lands · Ravines · Agroforestry systems · Ravine rehabilitation · Marginal lands · Ecosystem services

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7.1 Introduction

Degraded lands are characterized by decline in biomass production capacity as well as reduction in supply of goods and services from these areas due to either anthropological or natural causes. Degraded ecosystems face depletion of flora and fauna and loss of productivity due to either soil loss or other soil-related issues, low soil moisture availability, altered microclimate, high biotic interference or altered topography resulting in slow recovery during natural succession of vegetation. In India, an estimated 120.4 million hectares (Mha) suffer from various forms of land degradation due to water and wind erosion and other complex problems like alkalinity/ salinity and soil acidity due to waterlogging, out of which water erosion is predominant degradation class covering around 93 Mha area affecting more than 28% of total geographical area (TGA) of the country (ICAR 2010). These varying kinds of degradation mainly result from inappropriate land management practices. Among the various forms of land degradation, ravines are the worst manifestation of terrain deformation by water (Fig. 7.1).

The land degradation due to ravines is a major problem along several river systems in the alluvial zones. These may extend up to 2–3 km in to the tablelands, and vast areas go out of cultivation due to the process of degradation. It has been estimated that about 3.7 Mha of land has been affected by gully erosion along several river systems in the alluvial zones in India (Dhruva Narayan 1993). The ravine areas are most fragile ecosystem and are subjected to various kinds of natural resource losses and threat to biodiversity. Due to unregulated and over-exploitation, the natural vegetation in ravines is facing severe threats of losing biodiversity (Fig. 7.2).

Since land resources are finite, requisite measures are required to reclaim degraded and wastelands in ravine-infested region so that areas going out of

Fig. 7.1 Ravines are the worst manifestation of terrain deformation due to water

Fig. 7.2 A view of Yamuna ravines in Etawah district of Uttar Pradesh in India

cultivation are replenished by reclaiming these lands and arresting further loss of production potential. In India, trees have been planted or retained in the agricultural fields for centuries by the farmers. Agroforestry systems (AFS) have in recent past received renewed interest, particularly in developing countries (Young 1997; Dagar et al. 2014), as sustainable food production systems which are capable of reversing trends in land degradation. These systems play a vital role in the rural economy by way of tangible and intangible benefits and may potentially improve the economic potential of these lands through simultaneous production of food, fruit, fodder and firewood as well as mitigation of the impact of land degradation. These help in rehabilitation of degraded lands on one hand and increase farm productivity on the other. Dhyani et al. (2013) estimated the total area under agroforestry in India in the year 2013 as 25.32 Mha or 8.2% of the total geographical area of the country. They further suggested that a total of 53.32 Mha, representing about 17.57% of the total reported geographical area (TRGA) of India, could potentially be under agroforestry. Lands in ravine-infested areas may have huge potential for improved production potential, if placed under agroforestry land use in India (Dagar 2018a, b). Rehabilitation of ravine lands involves treatment of table and marginal lands contributing runoff to the gullies and economic utilization of gullied ravines. Various AFS may form part of an integrated approach for using gullies according to land capability classes, soil and water conservation measures and utilizing these lands by exploiting their available potential for providing various goods and services. Optimum utilization of suitable species of trees, shrubs and grasses is important in ravine rehabilitation efforts. Trees provide not only livelihood security but also services such as prevention of soil erosion, restoration of soil fertility and soil organic matter, control of salinity and protection of biodiversity.

7.2 Land Degradation Due to Ravines

The word 'ravine' means a deep gorge and represents the last stage of water erosion. The terms gully and ravine are often used as synonyms. Ravines are the systems of gullies running almost parallel to each other and draining into a river after a short distance with the development of deep gorges. These may extend up to 2–3 km into the tablelands, and vast areas go out of cultivation due to the process of degradation. Ravines may or may not have active streams flowing along the downslope channel which originally formed them. Ravines are typically classified as larger in scale than gullies, although smaller than valleys. The depth of small, medium and large gullies is <1, 1–5 and 5–10 m, respectively. Ravines are usually >10 m deep. Apart from land and soil quality degradation in gullied and inter-gullied areas and declined productivity for food, fuel, fodder and biomass, these sites are major sediment-producing hotspots. Out of the estimated 3.7 Mha ravine lands in India, major problem areas are located in Uttar Pradesh, Madhya Pradesh, Rajasthan, Gujrat and Bihar (Verma et al. 1986). The ravines occur along the Yamuna River and its tributaries; Gomati River and *kholas* of Ganga in Uttar Pradesh; Chambal River and its tributaries, Assan and Kalishindh in Madhya Pradesh; Chambal River and its tributaries like Kalishindh, Mej, Parvati, Banas, Parwan, etc., Banganga River and Sabi River in Rajasthan; and Mahisagar River, Narbada River, Sabarmati River, Watrak River, Saraswati River, Dhadhar River, etc. in Gujrat (Tejwani et al. 1975). Sharma (1980) classified the areas under ravines in five major zones based on morphological characters, erosion rates and intensity of ravines. There are four major areas of severe ravine erosion (Sharma 1980). The largest is the Yamuna-Chambal ravine zone. Ravines flank the Yamuna River for nearly 250 km and in the Agra and Etawah districts and may attain depths of more than 50 m. The Chambal ravines flank the main channel in a 10-km-wide belt which extends southward from the Yamuna confluence, some 480 km, to the town of Kota in Rajasthan. On the probable origin of ravines, Sharma (1980) suggested that a gully initiates along the animal trails, roads and paths on the agricultural uplands. On the other hand, ravine is a function of river action and begins along the river and encroaches upon the catchment area by headward growth. Another view is that both gullies and ravines are result of surface runoff mismanagement (Prajapati et al. 1982), especially deforestation, overgrazing and ill-considered tillage in an environment which is particularly susceptible to erosion (Kaul 1962; Tejwani 1959). This susceptibility is in part due to the intensity and concentration of rainfall during the monsoon (Singh et al. 1976; Babu et al. 1978; Raghunath et al. 1982) and in part due to the erodibility of the deep, alluvial soils where most of the ravines develop (Verma and Patel 1969; Narain et al. 1979). However, the unscientific land use practices leading to a disturbance of the hydrological balance is one of the reasons. Dagar (2018a) discussed the probable processes of ravine formation and their control measures.

7.3 Ecological Details of Ravines

Ravine lands are characterized by three distinct parts, namely, ravine top or hump (irregular in size and shape), slope and bottom/bed. In general, the depth of ravines ranges from 1 to 20 m but may reach even more than 50 m (Roy and Mishra 1969). The climate of the ravine region is semi-arid to subhumid with annual average rainfall of 600–800 mm, which is mostly received from July to October in intense storms. The year has three distinct seasons: hot and dry summer (April to June), rainy monsoon (July to October) and cold and dry winter (November to March). The minimum and maximum temperatures may vary from 3°C to 47°C during winters to summer. During summers, the humidity is low and evaporation is very high (Bhushan and Saxena 1984; Singh et al. 1972, 1976; Prajapati et al. 1977; Prakash and Rao 1986; Verma and Singh 2015). In the ravine regions, the soils have poor physical conditions and fertility. The topsoils in the gullies are highly eroded, and the exposed subsoils are low in organic matter content. Soils of ravine zones in Uttar Pradesh and Gujrat are deep alluvial deposits having sandy to sandy loam texture having low water holding capacity. In these zones, U-shaped ravines occur. The soils of Chambal ravine regions in Rajasthan and Madhya Pradesh are less deep alluviums as compared to those in Yamuna and Mahi ravine region in Uttar Pradesh and Gujrat. These have silty clay loam to clay texture, and calcium carbonate content in these increases with increasing depth. These soils are prone to waterlogging when wet and to compaction when dry. The infiltration rates are low to moderate. In these zones, V-shaped gullies are formed with narrow beds as the soils in lower layers are resistant to erosion as compared to topsoil. The ravines are characterized by dominance of thorny species. Extremes of climatic and edaphic conditions result in low productivity in adjoining marginal lands also. Champion and Seth (1968) have classified the natural vegetation of ravines under type 6BC2: Northern tropical ravine thorn forests. The typical ravine vegetation consists of low growing type of coarse grasses, bushy shrubs and xerophytic trees. Sajwan (1975, 1976) and Prajapati (1995) have described the floristic wealth of Yamuna ravines. Parandiyal et al. (2000) and Balaji and Nitant (2002) also studied the floristic diversity of Chambal and Yamuna ravines, respectively. Dagar (2018b) and Uthappa et al. (2018) described the vegetation ecology and biodiversity of ravines and its' importance for controlling ravine extension.

7.4 Need for Protection and Restoration of Ravine Lands

Ravine lands must be protected from further degradation to ensure that unrestricted expansion of ravines does not engulf the adjoining lands. If left unattended, the ravine lands tend to ingress into the adjacent tablelands by headward extension, and vast areas of fertile lands go out of cultivation. Studies on the rate of ravine extension in Rajasthan, Gujrat and Uttar Pradesh have revealed that the area under ravines is extending incessantly. Prakash et al. (1987b) reported that the ravine extension rates vary from 0.730 to 0.865% per annum for the Chambal ravine system, while Tiwari et al. (1987) and Nema et al. (1982) reported higher rates of ravine extension, i.e. 10.31 and 18.7% per annum in Yamuna and Mahi ravines, respectively. Singh et al. (1966) considered a very conservative estimate of ravine extension to be at 0.175% per annum and warned that Rajasthan may lose 5500 ha of cultivated land every decade. Khan (1972) reported that ravines in Madhya Pradesh were increasing at 2.5% per annum. Thus, it is rightly said that extending ravines mark the footprint of death for the cultivator. A systematic method of ravine classification is necessary for evolving suitable methods of ravine erosion control and management. Different types of gully classification are being followed in the ravine-infested states of northern India. Tejwani (1968) has classified ravines into four classes and has taken depth, bed width and side slopes of the gullies. We can do little to alter climate, soil or topography, but we can do a lot to determine land use and manage runoff. Since conservation practices are designed to use land judiciously and manage runoff properly, they are our best opportunity to control soil erosion by water. Dagar and Singh (2018) have recently compiled a comprehensive account on greening of ravine lands describing ecology, biodiversity, formation and reclamation of ravine lands in different parts of the world, and much information has been gathered about rehabilitation of Indian ravines.

7.5 Potential for Economic Utilization of Ravines

The optimum utilization of ravine lands is also essential for exploiting their available potential for providing various goods and services and to achieve the various national objectives like reduction in regional inequalities and poverty, creation of income-generating and productive employment opportunities and improvement of ecological balance with a systematic and strategic approach for holistic development of these degraded areas. Barring the marginal and shallow gullied lands, which can be reclaimed economically and can be utilized for agriculture, most of the ravinous lands are not fit for cultivation of agricultural crops and are classified as nonarable lands. Tillage practices in these nonarable lands lead to accelerated erosion, thus adding to their fast degradation. The best scientific land use for these lands is to place them under tree- and grass-based production systems involving horticulture, hortipasture, silvopasture, energy plantation and plantation for timber or other forest produce. In the year 1976, the National Commission on Agriculture estimated an annual loss of ₹1570 million worth of food grains, fodder and firewood in the absence of judicious management of the ravine-infested lands. Considering the average inflation rate of 8.15% per annum, this loss could be in the tune of ₹39,117 million in the year 2017. The shallow ravines can be economically reclaimed for agriculture if resources for irrigation can be created. The medium and deep ravines which cannot be economically/ecologically reclaimed for agriculture, due to vulnerability to accelerated erosion and rapid land degradation during tillage, can augment supplies of fruits, fuelwood, fodder industrial timber, bamboo and other minor forest produce if utilized judiciously. In this situation, tree-based farming offers excellent opportunities because of several advantages.

7.6 Agroforestry: An Optimum Land Use System for Ravines

Agroforestry farming practices provide multiple benefits including high productivity and additional income while maintaining soil health (Kang et al. 1984; Dagar et al. 2014). The potential of agroforestry as a sustainable land use system that combines production with conservation of natural resources has been receiving greater attention during recent past. The revival of traditional AFS, introduction of more compatible agroforestry practices and improvement of existing practices are being addressed largely due to increasing demographic pressure; decline in area under productive forests; increasing demands of fuel, fodder and tree-based products; and increasing land degradation hazards. In AFS, there is emphasis on managing rather than reducing complexity related to both ecological and economic interactions between the trees and crops or livestock (Lundgren 1982). The balance between positive and negative interactions between the components determines the outcome and productivity of the system. Total productivity of AFS is usually higher than in monoculture systems due to complementarity in resource capture; i.e. trees acquire resources that the crops alone are not able to procure.

AFS in ravines focus on the wide range of trees grown on farms and other rural areas. Among these are nitrogen-fixing trees for land regeneration, soil health and food security; fruit trees for nutrition; fodder trees for livestock; trees for timber, shelter and fuelwood; medicinal trees to cure diseases; and trees for minor products, viz. gums, resins or latex products. Most of these trees are multipurpose, providing a range of benefits. The major advantages of these tree-based farming are the ability of tree species to withstand harsh agroecological conditions such as moisture stress and tolerance to various degrees of salinity. Trees can establish on poor soils and improve the soil productivity through deep root system, recharging of groundwater, recycling of mineral nutrients from lower profiles of the ground, contribution of organic matter and improvement of microclimate by providing shade and checking the wind velocity. Agroforestry systems contribute to the sustainability of soil nutrient and water cycles and act as a buffer to climatic extremes. So, they are very important in maintaining sustainability of ecological system and sustainable development of socio-economic system (Rao and Reyes 1990; FAO 1999; Rao and Ong 2000). Thus, the agroforestry systems may be optimum land use in ravine region for providing desired protection against degradation while improving the capacity of these lands for providing various goods and services (Chaturvedi et al. 2014; Parandiyal et al. 2018).

7.6.1 Major Agroforestry Systems for Ravine Rehabilitation

The major agroforestry systems for ravine rehabilitation include systems that can be adopted in the marginal lands adjacent to ravines, systems for reclaimed shallow ravines and agroforestry systems for medium and deep ravines.

7.6.1.1 Agroforestry Systems for Marginal Lands Adjacent to Gullied Lands

As the major contributor of excess surface runoff to the gullies, marginal lands forming the catchment of adjacent gullies in ravines are of utmost importance for soil and water conservation. For arresting the ingress of extending gullies into these lands, agroforestry practices can be used as important tools for reducing runoff and soil loss from agricultural watersheds. Normally, interest in the use of agroforestry practices and contour grass strips for various environmental benefits relates to their potential to increase infiltration, reduce runoff and reduce non-point source pollution. Agroforestry land uses as multi-strata systems, combined with litter cover and dense root systems, hold runoff when it first reaches the surface and subsequently promote infiltration. In an agroforestry system, the vegetation plays two major roles: (1) The fine root system holds soil in place, reducing susceptibility to erosion, and (2) plant stems act as barrier to runoff water, thus decreasing the flow velocity and consequently enhancing sedimentation. Agroforestry systems used in these marginal lands may be agrihorticultural or agri-silviculture systems.

7.6.1.1.1 Agrihorticultural Systems for Marginal Land

As soil moisture is a major limiting factor due to low and erratic rainfall coupled with dry hot summer, it makes crop cultivation a risky proposition in marginal lands adjacent to ravines. Agrihorticultural system having a fruit crop tolerant to these stress conditions opens up opportunity for the farmer to get more assured income. In an agrihorticulture system, usually fruit trees are grown in rows, and compatible field crops are cultivated as intercrops for optimum utilization of the land during initial establishment of fruit plantations. The fruit trees are also introduced on field boundary of the fields or are planted as scattered in the agriculture fields. Several fruit trees have been evaluated for marginal lands adjacent to ravines by the three research centres of the Indian Institute of Soil and Water Conservation working on ravines of Chambal-Mahi Yamuna river systems which cover the major ravine lands in the country. The fruit species found suitable for productive utilization of marginal lands of ravines include *ber* (*Ziziphus mauritiana*), gooseberry (*Emblica officinalis*), *bael patra* (*Aegle marmelos*), *lasoda* (*Cordia dichotoma*), *karonda* (*Carissa carandas*), *chiku* (*Achras zapota*), mango (*Mangifera indica*), *kagzi* lemon (*Citrus aurantifolia*), kinnow mandarin (*Citrus reticulata*) and guava (*Psidium guajava*) etc., as they are compatible with most field crops. They can withstand the low-resource conditions well. Knowledge of marketing avenues and dedicated management for profitable disposal of produce is needed for large-scale adoption of any agrihorticultural system. In contrast to food crops, which have ready markets, the market of fruits is more specialized and depends largely on postharvest processing, speedy disposal of produce, infrastructure for rapid transportation, etc. These aspects are needed to be taken care of while adopting any agrihorticultural system in ravines, which may not have very good connectivity to major markets of the country. There are some important case studies in Chambal and Yamuna ravines:

(a) Studies conducted by IISWC Research Centre, Kota and Agra, in Chambal and Yamuna ravines reported that gooseberry, *kagzi* lemon and guava-based agrihorticulture land uses are suitable for ravine region (Balaji et al. 2002; Parandiyal et al. 2005). Block plantation of gooseberry (*cv* NA 7) was raised at a spacing of 10 m × 10 m, and cultivation of field crops was taken up in the interspaces of the tree rows. Field crops could safely be raised for the first 4 years. Later on, field crops could be changed to include shade-loving crops like ginger (*Zingiber officinale*), turmeric (*Curcuma longa*) or colocasia (*Colocasia esculenta*). Kagzi lemon was raised at a spacing of 6 m × 6 m, and cultivation of field crops was taken up in the interspaces of the tree rows. Guava (*cv* L-49, Allahabad *safeda*) was raised at a spacing of 8 m × 8 m, and field crops such as green gram (K 851) (*Vigna radiata*), soybean (JS 335) (*Glycine max*) and sesame (RT 46) (*Sesamum indica*) were cultivated successfully in the interspaces of planted trees with regular agronomic practices. The cost of developing the fruit plantation varied from ₹22,780 per ha (with intercultural cost for a 5-year period) in gooseberry to ₹26,450 in guava and ₹28,230 in lemon at prices of 2013. The average returns from the fruit trees were ₹84,000 per ha per annum in gooseberry, ₹120,000 (at 2013 prices) per ha per annum in guava and ₹90,000 from lemon on full maturity with fruiting starting from the fourth year of planting in these species. The yield of soybean grown in association with different fruit trees ranged from 933 kg with guava to 981 kg with lemon in the initial stages of plantation. The yield of *Sesamum* ranged from 583 kg with guava to 614 kg with lemon trees in the initial stages of plantation, and the yield of green gram ranged from 773 kg with guava to 794 kg with lemon trees in the initial stages of plantation. These systems can be suitably applied in marginal lands along the ravines and reclaimed shallow ravines in the all ravine systems.

(b) Similarly, studies conducted by IISWC Research Centre, Agra, to evaluate suitable intercrops for fruit plantations in Yamuna ravines in Agra reported better vegetative growth in Kinnow mandarin as compared to *Mosambi* irrespective of intercrops grown (Kumar and Srivastava 1998). Plantations of Kinnow mandarin and *Mosambi* were raised at a spacing of 5 m × 5 m. Spinach (Spinacia oleracea), fenugreek (*Trigonella foenum-graecum*), mustard (*Brassica juncea*) and potato (*Lycopersicum tuberosum*) were grown as intercrops in *rabi* (winter); watermelon (*Citrullus lanatus*), lady's finger (*Abelmoschus esculentum*), brinjal (*Solanum melongena*) and *lobia* (*Vigna unguiculata*) in *zaid*; and green gram in *kharif* season. Maximum fruit yield (3828 kg ha^{-1}) in *Mosambi* was obtained with fenugreek as the intercrop followed by spinach. The maximum yield of intercrops grown in both the fruit crops was recorded for spinach (16,000 and 8400 kg ha^{-1}) and minimum for potato (10,400 and 5600 kg ha^{-1}). Balaji et al. (2002) assessed the performance of gooseberry fruit trees and intercrops in reclaimed ravines in class II and class IV lands. Maximum (1352 kg ha^{-1}) yield of *rabi* mustard along with maximum moisture conservation (15.8 cm in 100 cm profile at 32 days after sowing) was obtained in plots where green manuring involving sunhemp (*Crotalaria juncea*) was taken up prior to sowing of mustard.

(c) Usually, the yield of field crops is considerably affected when they are grown in association with tree crops. Competition in the root zone for moisture and nutrients is the major reason for such antagonistic effects. A suitable root management practice would be able to minimize the adverse effects of tree crops on the field crop. Studies for evaluating different root management options were conducted at ICAR-IISWC, Research Centre, Agra, India. Five tree root management options, viz. T_1, tree planted in bottomless used bitumen drums of 90 cm height and 25 cm radius; T_2, tree planted in polythene (120 μ thick) lined pits; T_3, trenches (30 cm wide and 40 cm deep) in two sides of trees; T_4, trees without root management; and T_5, crop without ber (*Ziziphus mauritiana*) trees, were evaluated in Ber + pearl millet-wheat sequence in semi-arid Indo-Gangetic alluvium soils of Yamuna ravines from 1988 to 2001 (Prakash and Kumar 2001; Prakash et al. 2001). Trees planted in bottomless bitumen drums produced significantly higher fruit yield (7347 kg ha^{-1}), tree volume (35.1 m^3) and firewood (2180 kg ha^{-1}). All tree root management options improved crop yield over control (T_4). However, tree root management options (except T_1) decreased fruit yield than control.

7.6.1.1.2 Boundary Plantation Systems for Marginal Lands

Retaining and/or planting of multipurpose trees along the field boundary is a common tradition in the semi-arid tropics and more so in the lands adjacent to ravines. Apart from providing fuel, fodder and shade for animals, these trees are maintained as assets to provide revenues at maturity. The trees raised under this system shall be amenable to lopping with less spreading crowns and preferably shall have deep-rooted systems. Depending on the width of field, the tree rows are planted on field bunds constructed at 30 m or more distance apart. The tree-to-tree distance is adopted based on the species chosen for planting. The trees which could be grown along the boundary in ravine region included *Acacia nilotica*, *Acacia leucophloea*, *Leucaena leucocephala*, *Azadirachta indica*, *Albizia lebbeck*, *Soymida febrifuga*, *Salvadora oleoides*, *Tecomella undulata*, etc. Plantation of Karonda (*Carissa carandas*) was found profitable and acted as live fence because it bears sharp thorns and forms thick hedge. These trees are compatible for use in boundary plantation with most of the crops grown in ravine regions. For example, castor (*Ricinus communis*) (var. Aruna, GAUCH-1, GCH-4) and pigeon pea (*Cajanus cajan*) (var. Prabhat, IPCL-151) were found compatible for these boundary plantation systems.

7.6.1.2 Case Studies

In a study of boundary plantation system in marginal lands of Chambal ravines at Kota, Parandiyal et al. (2008) reported better returns in a system comprising of boundary plantation of *Acacia nilotica*, *Azadirachta indica* and *Albizia lebbeck* in association with field crops of castor and pigeon pea. The average yield of castor in marginal lands of ravine region ranged from 600 to 1000 kg per ha, and yield of pigeon pea was 700–1000 kg per ha. The average reduction in castor production in association with trees varies from 4% in association with *Acacia nilotica* to 5.4% with *Albizia lebbeck*. In 2014, the price of pigeon pea was ₹43,500 per Mg, and market price of castor was ₹42,000 per Mg. The returns from fuelwood production by trees varied from ₹25,260 in *Acacia nilotica* to ₹30,240 per ha in *Albizia lebbeck* in a rotation of 12 years at 2014 prices. Production of fodder at 3–5 Mg ha^{-1} $year^{-1}$; bioinsecticides; timber on tree maturity if trees are not harvested early; yield of by-products like tannins, etc.; and soil amelioration due to addition of soil nitrogen are added advantages.

Case Study 2

A drumstick (*Moringa oleifera*)-based plantation system was evaluated for marginal lands in ravine regions of Gujarat (Singh and Pande 2010). Economic analysis of *Moringa oleifera* and *Emblica officinalis* (aonla)-based agrihorticulture trees with *Phaseolus radiates* and *Foeniculum vulgare* crops was also carried out (Pande et al. 2018). Drumstick is a rain-fed horticultural crop and does not require additional irrigation water for normal growth and development. Drumstick plant is a highly valuable plant with exceptional nutritional properties. The leaves are highly nutritious and a significant source of beta-carotene, vitamin C, protein, iron and potassium. The fresh leaves are cooked and used like spinach, and the dried ones are crushed into a powder and used in soups and sauces. It has been used successfully to combat malnutrition among infants and women of childbearing age. The leaves, roots, seed, bark, fruit, flowers and immature pods act as cardiac and circulatory stimulants and possess antitumor, antipyretic, antiepileptic, anti-inflammatory, antiulcer, antispasmodic, antihypertensive, antioxidant, antidiabetic, antibacterial and antifungal activities. Pruned leaves are nutritious and used as fodder. Air-dried stems and branches are used as fuelwood. Aonla/gooseberry is used in various forms as food as well as for medicinal purpose. This is marketed in different forms such as pickle, candy and dried powder. Introduction of tree component with traditional crops on such marginal lands is beneficial not only in terms of short-term profitability but also resource conservation. Drumstick (*Moringa oleifera*) *cv*-PKM1 and grafted aonla (*Emblica officinalis*) *cv*-NA7 seedlings were transplanted in standard size pits dug at 4 m× 16 m and 7 m× 8 m spacing, respectively, as alley cropping system in green gram-fennel cropping systems. After green gram (*Phaseolus/Vigna radiata*) *cv*-K852 crop in *kharif* season, fennel (*Foeniculum vulgare*) *cv*-GF1 crop was taken in *rabi* as intercrops. Perennial species, *Moringa oleifera* and *Emblica officinalis*, were raised on pits of 75 cm × 75 cm × 75 cm in size in the month of July after good soaking rains and saturation of soil profile. Drumstick was pruned every year up to the height of 1.75 m in the middle of June and had little shade effect especially on kharif crop of green gram. Green gram was grown during kharif season as a rain-fed crop. Seed at the rate of 12–15 kg per ha was directly sown at a row spacing of 40 cm with a plant-to-plant spacing of 10 cm. Fennel was grown as an alley cropping system. The study reported the net returns of ₹31,079 ha^{-1} (at 2009–2010 prices) from drumstick + green gram-fennel cropping system. Enterprise budgeting analysis revealed that the net present values from

M. oleifera + *P. radiata* followed by *F. vulgare* and *E. officinalis* + *P. radiata* followed by *F. vulgare* were 386 and 1190 US$ ha^{-1}, respectively, at 2012–2013 local prices over a production cycle of 15 years (Pande et al. 2018). Saving in soil nutrients and soil carbon build-up worth 12–240 and 665 US$ ha^{-1} was observed. Further, the land expectation value of *E. officinalis*-based agrihorticulture production system (1564 US$ ha^{-1}) revealed higher land value as compared to tobacco monocropping system (1039 US$ ha^{-1}). While the financial viability of these cropping systems proved their worth on the marginal lands of ravines in Gujarat, market and yield risks in crop component, examined through sensitivity analysis, need to be taken into consideration before recommending the agrihorticultural system to farmers.

7.6.1.3 Agroforestry Systems for Reclaimed Shallow Ravines

Most of the AFS adopted in marginal lands adjacent to ravines can be effectively utilized for economic utilization of reclaimed shallow ravines. As usually the reclaimed shallow ravines have relatively less compact soils, they are prone to accelerated erosion if protective measures are not adopted. The bunds of these fields must be reinforced with planting of grasses and shrubs/multipurpose trees. The reclaimed shallow ravines shall preferably be protected by raising peripheral bunds to allow safe disposal of excess runoff through designated weirs into the adjacent gullies. These peripheral buds can be protected by sodding of grasses, preferably fodder grasses like *Dichanthium annulatum*, *Cenchrus ciliaris*, *Cenchrus setigerus*, *Panicum maximum*, etc. and planting of shrubs like *Agave americana*, *Carissa carandas*, *Cassia angustifolia*, *Cajanus cajan*, etc. and/or multipurpose trees especially those used for fuel and leaf fodder. If terracing has been carried out in shallow ravines, grass planting/sowing is carried out to protect the ridges of terraces. In case facilities for irrigation can be developed, these shallow ravines can economically be utilized for raising field crops/agrihorticulture or horticulture land uses.

7.6.1.4 Agroforestry Systems for Medium and Deep Ravine Lands

As the medium and deep ravines are highly vulnerable to accelerated degradation, if tillage operations disturb the soil stability, they are unsuitable for tilling for agricultural crop cultivation, and most of the times, these cannot be reclaimed economically by terracing and/or land levelling. Even if these medium and deep ravines are levelled with substantial cost, the hydrological stability of reclaimed land remains questionable. Therefore, placing these under permanent vegetation, where periodic tilling of land is not required, may be the more suitable scientific land use for these medium and deep ravine lands. Silvopastoral land use, involving cultivation of multipurpose trees with interplanting of palatable grasses, is an important production system for economic utilization of medium and deep ravines. It aims at augmenting production of fuelwood while utilizing the interspaces of planted trees for production of fodder grasses (Figs. 7.3 and 7.4).

Multipurpose tree species such as *Acacia nilotica*, *Acacia leucophloea*, *Ailanthus excelsa*, *Bauhinia variegata*, *Leucaena leucocephala*, *Azadirachta indica*, *Albizia lebbeck*, *Soymida febrifuga*, *Salvadora oleoides*, *Tecomella undulata*, *Pongamia*

Fig. 7.3 Ber + *Aloe vera* agrihorticulture system in reclaimed Yamuna ravines

Fig. 7.4 *Azadirachta indica* + *Cenchrus ciliaris* silvopastoral system in Chambal ravines of India

pinnata, *Melia azedarach*, *Erythrina indica*, *Holoptelea integrifolia* and *Dalbergia sissoo* are suitable for use in medium and deep ravines. Locally available promising grasses like *Dichanthium annulatum*, *Cenchrus ciliaris*, *Cenchrus setigerus*, *Sehima nervosum* (rat's tail grass), *Panicum maximum* (guinea grass) and *Chloris gayana* (Rhodes grass) can successfully be cultivated in interspaces of the multipurpose trees. As ravine lands are generally owned by resource-poor farmers, trees primarily used for fuel and fodder receive better acceptability among farmers of ravine region. Dagar (2018a, b) has mentioned several perennial grasses and legumes naturally growing in ravine lands and can be protected from grazing or cultivated with trees for viable fodder production. Species such as *Dichanthium annulatum*, *D. caricosum*, *Heteropogon contortus*, *Themeda triandra*, *Iseilema laxum*, *Chrysopogon fulvus*, *Sehima nervosum*, *Cenchrus ciliaris* and *Panicum* species are quite suitable for ravine lands in India.

7.6.1.5 Case Studies

(a) Staggered trenching for runoff conservation in horti-pasture system
As moisture is one of the major constraints for development of vegetation in ravines, rainwater harvesting and runoff trapping measures improve the survival and growth of planted fruit trees in ravines. Staggered trenching for excess runoff water harvesting is important measure for facilitating improved survival and growth of planted vegetation in marginal lands and humps of ravines (Fig. 7.5).

To assess the efficacy of staggered trenching and evaluate the suitability of gooseberry-based pastoral system for Chambal ravines, a study was carried out from 2006 to 2011 at ICAR-IISWC, Research Centre, Kota (Sethy et al. 2011). The soils of the study site were very deep clay loam in texture, low in organic carbon, available nitrogen and phosphorus but medium to high in potash with a slightly alkaline pH. The climate is semi-arid tropical with an average annual rainfall of 789 mm, mostly received during July to September, while almost 8–9 months are dry. Four ravinous micro-watersheds ($RW_1 = 0.4$ ha, $RW_2 = 1.4$ ha, $RW_3 = 1.1$ ha and $RW_4 = 1.0$ ha) were treated with four different trenching densities (i.e. 0, 25, 50 and 75% runoff trapping potentials), i.e. no trenches, 139 trenches ha^{-1}, 278 trenches ha^{-1} and 417 trenches ha^{-1} with uniform size of 3.0 mm × 0.6 m × 0.45 m. A uniform land use management system applied in all the micro-watersheds included fruit tree gooseberry (*Emblica officinalis*) on ravine humps, bamboo on gully beds and interspaces with *Cenchrus ciliaris* grass. The numbers of plants were kept in 278 ha^{-1} with spacing of grass slips at 0.5 m × 0.5 m. After 6 years of planting in ravines, the total productivity of ravinous lands was observed as 3.90, 4.52, 6.31 and 8.53 Mg ha^{-1} $year^{-1}$ and fruit equivalent under RW_1, RW_2, RW_3 and RW_4, respectively. While the production of fruit ranged from 1.31 Mg ha^{-1} in control (no trenches) to 6.61 Mg ha^{-1} in treatment involving trenching for trapping 75% runoff, the production of grass ranged from 7.71 to 9.91 Mg ha^{-1}. Results showed mean runoff reductions of 86.1, 60.5 and 37.7% in the RW_3, RW_2 and RW_1

Fig. 7.5 Staggered trenching for runoff harvesting in ravines helps in establishment of planted vegetation

treatment watershed over the control, respectively. Similar trends as the runoff were also recorded in soil loss reduction by 124.9, 77.1 and 40.0% for the RW_3, RW_2 and RW_1 over RWc, respectively. Paired *t*-test ($p < 0.001$) indicated that the means of the treatment effects on runoff and soil loss in treatment watersheds differ significantly with control watershed. It was concluded that 417 staggered contour trenches ha^{-1} is an optimum trenching density for supporting the fruit-based pastoral land use system in ravine lands of India (Ali et al. 2017). Thus, the trenching at 75% runoff trapping potential density proved superior to others in terms of moisture conservation (87.3%), reduction in runoff (78.23%) and soil loss (90%) and improved production potential (218.7%) of ravinous lands under medium and deep ravinous lands.

(b) Evaluation of Underutilized Fruit Species for Suitability in Chambal Ravines

Underutilized fruits or minor fruits are hardy fruit species with high potential for use in economic utilization of degraded lands. In a study carried out from 2006 to 2014 for evaluation of underutilized fruit species for suitability in Chambal ravines, four underutilized tree species, namely, *Aegle marmelos* (cv. N.B. 5), *Cordia myxa* (cv. *Puskar*), *Annona squamosa* (cv. *Mammoth*) and *Carissa carandas* (cv. *American Red*), were evaluated under a hortipastoral system (Meena et al. 2015). The study aimed at generating information on suitability and production potential of underutilized fruit species in ravinous degraded lands as well as the efficacy of half-moon-shaped microcatchment shaping treatment with and without interplanting of grasses. The experiment was conducted with four fruit species and four interspaces management, viz. clean tilled, clean tilled with microcatchment shaping, microcatchment shaping with *Cenchrus ciliaris* and microcatchment shaping with *Dichanthium annulatum*. The fruit species were planted with standard spacing bael (*Aegle marmelos*) at 8 m × 8 m; lasoda (*Cordia myxa*) at 6 m × 6 m; custard apple (*Annona squamosa*) at 4 m × 4 m and Karonda (*Carissa carandas*) at 2 m × 2 m spacings. Both the grasses *Cenchrus ciliaris* and *Dichanthium annulatum* were planted with 30 cm × 30 cm spacing in interspaces of trees as per treatments. The treatments were imposed on the hump top of the ravine area. *Carissa carandas* recorded 100% survival followed by *Cordia myxa* (97%), *Aegle marmelos* (96%) and *Annona squamosa* (46%) after 2 years of planting. All four species recorded maximum height when planted under clean-tilled condition with half-moon shaping treatment. It was followed by clean-tilled microcatchment shaping with *D. annulatum* and microcatchment shaping with *C. ciliaris* grass, respectively. In the initial fruiting stage, the highest yield was recorded in Karonda (3.3 Mg ha^{-1}) because of early fruiting and highest number of plants accommodated in per unit area in all treatments followed by bael (3.0 Mg ha^{-1}), lasoda (1.5 Mg ha^{-1}) and custard apple (0.7 Mg ha^{-1}), respectively. After 8 years of planting, the average grass cover of *Cenchrus ciliaris* was 78%, while *Dichanthium annulatum* recorded 71% average grass cover in their respective treatments. The cover of both grasses was lowest (58% in *Dichanthium annulatum* and 65% in *Cenchrus ciliaris*) when planted with *Lasoda* due to its spreading type of growth behaviour and it was highest (75% in

Dichanthium annulatum and 86% in *Cenchrus ciliaris*) with custard apple. *Cenchrus ciliaris* provided higher average annual grass yield (8.31 Mg ha^{-1} dry) than *D. annulatum* (8.02 Mg ha^{-1} dry weight) for a 3-year period. Thus, *Carissa carandas*-, *Cordia myxa*- and *Aegle marmelos*-based pastoral hortipastoral systems are considered successful in Chambal ravines.

7.6.2 Ecosystem Services of Agroforestry Systems in Ravines

Ravine lands are vulnerable to accelerated degradation if they are not optimally utilized. AFS provide opportunity for economic utilization of ravine lands while making best use of the protection potential of vegetation against soil erosion and land degradation. The environmental services offered by agroforestry include substantial contribution towards carbon sequestration, soil erosion control, reduced risk of leaching, improvement in the nitrogen balance through legumes, improved soil properties, enhanced biodiversity and improved microclimate. Trees in AFS provide important ecosystem services, including soil, spring, stream and watershed protection, animal and plant biodiversity conservation and carbon sequestration and storage, all of which ultimately improve food and nutritional security (Garrity 2004). AFS have the potential for improving biodiversity (Atta-Krah et al. 2004). In agroforestry, the improved biodiversity results from provision for habitat and resources for wide range of plant and animals, reducing the rate of conversion of natural habitat, conservation of native flora and fauna and improving habitat by reducing degradation processes. The adoption of AFS in ravine lands leads to improved microclimate, improved soil moisture, reduced runoff and soil loss, improved soil properties, enhanced vegetation cover and ultimately arresting the degradation processes. The resultant improvement in production potential leads to enhanced value of land. The three research centres of ICAR-Indian Institute of Soil and Water Conservation in various studies reported considerable reduction in the runoff and soil loss from the ravine lands if placed under agroforestry systems.

7.6.2.1 Potential of Agroforestry for Carbon Sequestration in Ravine Region

Although AFS may reduce crop yield for a variety of reasons, there may be a trade-off. Recent evidences suggest that AFS are promising management practices to increase aboveground and soil C stocks to mitigate greenhouse gas emissions. Land management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere if the trees are harvested, accompanied by regeneration of the area, and sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood. Carbon management through afforestation and reforestation in degraded natural forests is a useful option, but agroforestry is attractive because (1) it sequesters carbon in vegetation and possibly in soils depending on the pre-conversion soil C; (2) the wood products produced under agroforestry serve as a substitute for similar products unsustainably harvested from the natural forest; and (3) to the extent that agroforestry increases the income of farmers, it reduces the incentive for further extraction from the natural forest for income augmentation. The incorporation of trees or shrubs in AFS can increase the amount of carbon sequestered compared to a monoculture field of crop plants or pasture (Sharrow and Ismail 2004; Kirby and Potvin 2007). AFS have substantial potential for carbon storage and sequestration (Montagnini and Nair 2004), and it can also be a tool for minimizing nutrient losses from well-fertilized soils. In India, average sequestration potential in agroforestry has been estimated to be 2 Mg C per ha over 96 Mha, but there is a considerable variation in different regions depending upon the biomass production. However, compared to degraded systems, agroforestry may hold more carbon. Ravine lands have very high potential for carbon sequestration through agroforestry land use as the existing natural vegetation in these lands is sparse. Singh et al. (2016) reported that the organic carbon status of ravines soils is poor and mostly in active pool while passive pool is deprived of carbon. They also suggested that plantation under different AFS helps to increase organic carbon in soil. These studies suggest that highest biomass accumulation was under hortipastoral system followed by agrihorti system, silvopastoral systems, silvi-medicinal system and diversified cropping system, respectively. There was significant increase in soil organic carbon from 0.11 to 0.35% under various agroforestry systems in three periods of study.

In a study conducted at ICAR-IISWC, Research Centre, Kota, two fruit-based pastoral systems and two silvopastoral systems along with three natural forests were examined during 2011–2015 (Parandiyal et al. 2016). At the on-farm site in ICAR-IISWC, Research Centre, Kota, two existing hortipastoral systems, namely, Beal + Dhaman (*Aegle marmelos* + *Cenchrus ciliaris*) and Amla + Dhaman (*Emblica officinalis* + *Cenchrus ciliaris*), and two silvopastoral systems, namely, Desi babool + Dhaman (*Acacia nilotica* + *Cenchrus ciliaris*) and Karanj + Dhaman (*Pongamia pinnata* + *Cenchrus ciliaris*), were studied. The study site represented the typical Chambal ravines and was located in district Kota of Rajasthan. Another off-farm study sites of three natural forests consisting of (1) Sahpur forest, (2) Mamoni forest (3) Kaloni forests, located in Shahabad range-Baran division were also studied. All kinds of vegetation were inventoried at both study sites through sample plots for preparing inventory map depicting top storey (trees), middle storey (shrubs) and ground flora (grasses + herbs). Periodic observations on the biomass growth and litter production characteristics of the vegetation and soil carbon stock estimation were recorded under different land uses. The vegetation in the on-farm site comprised of top storey of the tree species planted and ground flora dominated by *Cenchrus ciliaris* and annual herbs. Off-farm site in the natural forest consisted of three different strata. The composition of ground, middle and top flora was assessed through sample plot systems. The detailed inventory map was prepared based on phytosociological compositions of vegetation under three natural forest sites. The highest litter production was recorded in *Acacia nilotica* (6.23 Mg ha^{-1}) followed by *Aegle marmelos* (5.66 Mg ha^{-1}), while the lowest litter production was recorded in *Pongamia pinnata* (3.92 Mg ha^{-1}) in agroforestry systems. In the natural forest, the highest litter production was recorded in *Boswellia serrata* (9.02 Mg ha^{-1}),

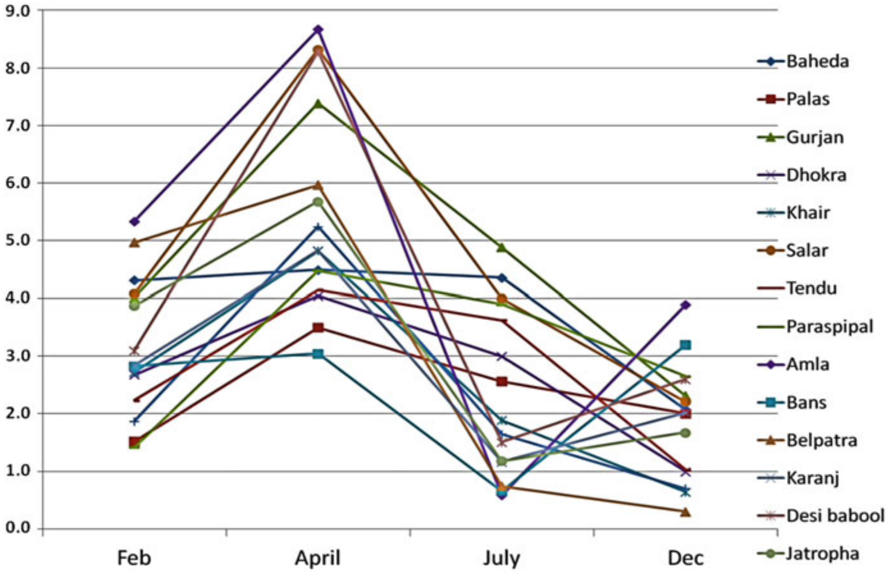

Fig. 7.6 Litter production (Mg ha^{-1}) by different tree species in south-eastern Rajasthan

while the lowest litter production was recorded in *Acacia catechu* (1.62 Mg ha^{-1}) (Fig. 7.6).

The rates of litter decomposition were highest in *Acacia nilotica*, *Acacia catechu* and *Emblica officinalis* (07 months for 99% decomposition), while it was lowest in *Terminalia belerica*, *Buchanania cochinchinensis* and *Diospyros melanoxylon* (11 months for 99% decomposition). Among all systems studied, the total carbon in biomass (751.62 Mg ha^{-1}), total carbon stock (770.55 Mg ha^{-1}) as well as total CO_2 sequestration (2827.90 Mg ha^{-1}) were highest in the *Acacia nilotica*-based silvopastoral system. In the natural forest, total carbon in biomass (214.57 Mg ha^{-1}), total carbon stock (232.59 Mg ha^{-1}) as well as total CO_2 sequestration (853.60 Mg ha^{-1}) were highest in the Mamoni natural forest at Shahabad range in Baran division. Lal (2018) and Somasundaram et al. (2018) also described the potential of ravines for carbon sequestration.

7.6.2.2 Soil and Water Conservation Potential of Agroforestry in Ravines

The sloping lands like ravines are characterized by high runoff and soil loss as soil moves due to gravity with the runoff water and displacement by splash action of raindrops. Tree cover provides most effective barrier to splashed induced soil erosion as lower canopy leaves and leaf litter are capable of dissipating kinetic energy of the falling raindrops. The AFS as multi-strata systems, combined with litter cover and dense root systems, hold runoff when it first reaches the surface and subsequently promote infiltration. In an agroforestry system, the fine root system of vegetation holds soil in place, reducing susceptibility to erosion, and the plant stems

Table 7.1 Hydrological behaviour of ravine watersheds under forestry (RW1) and horticulture (RW2) land uses

Year	Rainfall (mm)	Runoff (% rainfall)		Soil loss (Mg ha^{-1} $year^{-1}$)	
		RW 1	RW 2	RW 1	RW 2
2006	817.5	21.58	23.39	7.45	8.13
2007	707.5	11.24	13.37	3.6	5.1
2008	617.5	9.17	11.2	3.4	4.53
2009	402.6	0	2.7	0	1.4
2010	398	0	0	0	0
2011	1058.1	9.96	12.35	3.34	4.48
2012	772.6	1.12	3.64	0.35	1.72
2013	1037	6.53	7.54	1.54	2.57
Mean	726.35	7.45	9.27	2.46	3.49

act as barrier to runoff water, thus decreasing the flow velocity, improving infiltration and consequently enhancing sedimentation. Land-protective functions of trees could be moderation of rain energy through canopy interception, litter effect and root reinforcement functions (Wiersum 1984, 1985). The multitier vegetation in AFS tends to intercept the falling raindrops and reduces the splash erosion on one hand while increasing the stem flow. The annual vegetation in the AFS acts as barrier to control unrestricted flow of surface runoff and reduce runoff volume by improving the infiltration due to increased time of concentration. As a result of less runoff and leaching, micro-watersheds with tree cover or AFS that cover a high percentage of the soil surface produce high-quality water. Several studies conducted in ravine lands reported the efficacy of tree-based production systems in controlling runoff and soil loss in nonarable ravine lands (Prajapati et al. 1982; Prakash et al. 1987b; Sharda et al. 1982; Yadav et al. 1988). Parandiyal and Meena (2014) in an 8-year study of MPT-based and fruit tree-based AFS in Chambal ravines reported significant reduction in runoff and soil loss from steeply sloping ravine watersheds under forest and fruit trees-based AFS (Table 7.1). Ali et al. (2014, 2017) also reported significant reduction in soil loss and surface runoff from gooseberry-based AFS in Chambal ravines.

7.7 Conclusion

Degraded lands, especially ravines, have gained importance with progressively declining per capita land availability in the country. Trees play an important role in rehabilitation of degraded lands and provide a range of products and services to humanity. In existing state, ravine lands are vulnerable to further degradation. Though most of the ravine-infested lands are too unfriendly for cultivation of high-value crops, they are potential areas for augmentation of supplies of fuelwood, fodder, fruits, timber and carbon sequestrations. The shallow ravines if reclaimed scientifically may contribute to food production. Various agroforestry systems have been evaluated and found suitable for use in ravine-infested areas. Integration of trees with fodder and industrial grasses, which are capable of sustaining during the moisture stress and extreme hot condition under resource-poor soils, can provide sustained economic returns from ravine lands while arresting their further degradation. Silvopastoral and fruit-based agroforestry systems involving species of dry areas are the most appropriate options for the rehabilitation of ravine lands. These agroforestry systems also have huge potential for carbon sequestration and soil amelioration.

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Urban and Peri-Urban Agroforestry: Utilization of Wastewater and Degraded Landscapes for Environmental and Livelihood Security

8

Khajanchi Lal, Denny Franco, K. G. Rosin, and R. K. Yadav

Abstract

Urban agroforestry systems are integration of grey and green technologies, capable of recycling and reusing of wastewater and conserving nutrients into biomass, thereby bringing multiple benefits such as fuelwood production, environmental sanitation and eco-restoration. Being an immense source of nutrients and due to its dependable availability, urban and peri-urban farmers can rely on treated wastewater as an alternative source for irrigation in the current water stress scenario. Nevertheless, wastewater contains toxic organic chemical, heavy metals and pathogens which may hamper its use for direct application in food crops. Irrigation of tree plantations with wastewater for fuel and timber production is an approach which helps to overcome health hazards associated with wastewater farming. Integration of food crops with tree species helps to effectively utilize the renewable energy sources and provide additional economic benefits apart from the complimentary services provided through crop production. Agroforestry along with wastewater irrigation helps to mitigate the climate change through carbon sequestration. Other direct benefits are prevention of erosion, regulation of freshwater flows, cooling of terrestrial surfaces, maintaining soil fertility, solution for energy requirements and increased availability of forest products. Still the adoption of urban and peri-urban agroforestry systems by farming community is fewer due to the lack of best-suited cropping system comprising shade-loving remunerative crops as well as poor performance of food crops in the system and ignorance of environmental-associated benefits. Proper intervention of policy support and awareness among the peri-urban farmers will boost the adoption of

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this integrated system for social, economic and environmental benefits. Wastewater has a huge untapped potential for resource recovery and reuse, in which along with agroforestry the benefits are much higher while considering the total economic value of forestry plantations and crops with their environmental services.

Keywords

Carbon sequestration · Irrigation · Tree plantations · Urban effluents · Urban and peri-urban agroforestry

8.1 Introduction

Water scarcity and escalating demand from other sectors hassled the availably of freshwater for irrigation in agriculture, which consumes 70% of freshwater globally. Higher allocation of freshwater to rapidly growing population along with urbanization and industrialization prompts the generation of huge volumes of wastewater which is a hurdle for the local institution and the environment. In most of the countries, wastewater produced from residential and industrial establishments and runoff water produced from rain are disposed in the common drainage cum disposal channel. These wastewaters are rich in essential plant nutrients but also contain salts, pathogens, heavy metals and other pollutants, which impair quality of natural resources, contaminate food chain and pose serious threat to human and animal health. Regulated use of these wastewaters after suitable treatment is a reliable alternative for water scarcity, enhances soil fertility, preserves natural resources, develops local products and improves living conditions of urban and peri-urban farmers (El Moussaoui et al. 2019). About 20 million ha of land in 50 countries is irrigated using raw or partially diluted wastewater (Raschid-Sally and Jayakody 2008). Treating huge streams of wastewater before as per guidelines is prohibitively expensive for most of the low- to middle-income developing countries. Only 35% of wastewater is treated in Asia, 14%in Latin America and only a negligible portion in Africa (Scott et al. 2006). Out of total 61,754 MLD of municipal wastewater generated in India, only 22,963 MLD (i.e. about 38%) can be treated with the present capacity, and the remaining 38,791 MLD (62%) is disposed either in surface waterbodies or on land with no or little treatment (CPCB 2016). Where regulations and treatment processes are not adequate, these untreated waste streams are used for irrigation in high-value crops including vegetables, horticulture and food grains. Use of untreated wastewater pollutes our valuable natural resources and contaminates food chain with pathogens and toxic chemicals, thus posing potential health hazards (Minhas and Samra 2004; Gupta et al. 2008; Drechsel and Evans 2010; Drechsel et al. 2010; Yadav et al. 2015).

One option which can help in overcoming health hazards associated with wastewater use can be its application for irrigating tree species grown for fuel and timber and developing green belts around the cities (Thawale et al. 2006). Tree plantations generally have higher water use compared to annual crops because of aerodynamic roughness, clothesline effect in tree rows and deeper rooting system for accessing water down. In developing countries, farmers have small holdings which are the only source of livelihood. They cannot afford to put the land under tree plantations which yield after a gap of 5–6 years. Under such situations, agroforestry or systems comprising of fast-growing short-duration woody perennials having deep root system and high transpiration capacity are preferred because higher volumes of wastewater can be disposed off in these systems and they provide regular income to the farmers. Moreover, tree plantations -based mixed species production systems cosisting of crops suitable for sewage farming, avoid degradation of natural resources through interactions among trees, soil, crops, and livestock. Land application of wastewater in agroforestry systems facilitates the wastewater treatment as the soil acts as a living filter having its own rejuvenation capacity and recycles and converts nutrient into biomass, thereby bringing multiple benefits such as soil fertility improvement, higher crop productivity, fuelwood, environmental sanitation and eco-restoration. For safe and sustainable use of wastewater, loading rates of wastewater and its constituents should match the water and nutrient requirements of proposed plantations and associated crops. Apart from those direct benefits, afforestation programmes through wastewater irrigation help to mitigate the climate change through carbon sequestration. Other benefits associated with agroforestry are soil conservation, water replenishment, solution for energy requirements, increased availability of forest products, boosting of livestock sector and many more. Despite such advantages, agroforestry as a land use option has not attracted much attention from the planners and extension community. Reasons for this include inconsistencies in understorey crop productivity, ignorance of environmental benefits and lack of public policy support. Conscious efforts on system management and policy adjustments are, therefore, imperative to promote agroforestry adoption to experience its overall advantages by the farming community. Keeping above in view, agroforestry development, benefits of agroforestry systems, suitable trees and crops for wastewater-irrigated agroforestry system, tree species having higher transpiration rates for wastewater disposal, C sequestration and ecosystem services and way forward to realize social, economic and environmental benefits of urban and peri-urban agroforestry are discussed in this chapter.

8.2 Agroforestry Development

Agroforestry consists of all trees on farms, including woody shrubs such as saltbrush and tagasaste, grown in association with crops, pasture and livestock. Wood is typically the main product, but there is also potential for non-wood products such as nuts, seeds, oils and foliage. Agroforestry ecosystems have light, water, and nutrients pools that can be shared in horizontal, vertical, and time dimensions involving competitive, differential and complementary aspects.

Historically, agroforestry development involved two distinct pathways, viz. growing food crops in the forests and establishing tree crop production systems on arable lands. Just as the direct forms of production (e.g. edible fruits, nuts, grain, rhizomes and tubers, leaves, flowers, fodder, mushrooms, medicinal plants and other non-timber forest products including fuels, livestock products, etc.), the indirect mechanisms that promote enhanced and/or sustained production (soil fertility improvement, soil and water conservation, hydrological benefits, microclimatic modification, etc.) are fundamental to both types. Most agroforestry systems are also complementary to other crop production enterprises, as they provide green manure, fodder and fuel (Wiersum 2006). This complementary and sustainable use of environmental resources differentiates food production through agroforestry from that through intensive arable cropping and makes agroforestry particularly attractive.

Trees can generate substantial environmental gains in addition to any commercial returns and provide both an alternative enterprise and land and water protection. The environmental benefits are as follows (Binning et al. 2002):

- Soil stabilization and reduced wind and water erosion.
- Improved water quality.
- Wildlife corridors.
- Habitat protection.
- Salinity control.
- Improved aesthetics.
- Sequestration of carbon.
- Conservation of biodiversity.

8.3 Wastewater Characterization

Wastewater consists of effluents from municipalities, industries, commercial establishments and storm water. It is the water that has been used in domestic or industrial processes and its quality is deteriorated during the utilization process. Wastewaters contain mainly water (>95%) and other soluble and non-soluble constituents. The solid portion contains 40–50% organics, 30–40% inert materials, 10–15% bio-resistant organics and 5–8% miscellaneous substances on the oven-dry basis (Antil and Narwal 2008). Domestic municipal wastewaters generally have high salt content, organic load and nutrients and pathogen, while industrial wastewaters often also contain metals, metalloids and volatile compounds. The presence of heavy metals in wastewaters of different cities in India shows threat to human and environment.

The production of wastewater is directly proportional to the growth in population, urbanization and economic development. Management of wastewater needs a special attention for the sustainable growth in institutional perspective. The higher volume of wastewater will make the availability of water more economical in urban and peri-urban areas and lesser dependence on the energy-consuming conventional pumping systems. The use of this extra water in other sectors will reduce the competition for freshwater for irrigation. In the developing countries irrigation with raw wastewater or wastewater mixed with stream water is highly prevalent in the urban and peri-urban areas where fresh water for irrigation is not available. The irrigating edible crops with raw wastewater may leads to health hazards in both producers and consumers. But the institutional mechanisms to check these unhealthy practices are poorly developed or hardly in non-existence in these countries.

8.4 Suitable Tree Species and Crops for Wastewater-Irrigated Agroforestry

The indiscriminate and excessive use of untreated urban effluents causes a gradual accumulation of heavy metals in soil to the levels that might become toxic to plants, reduces crop yields and may pose public health hazards (Drechsel and Evans 2010; Najam et al. 2015; Wang et al. 2015; Yadav et al. 2015). Use of treated wastewater close to human settlements or immediately downstream of the wastewater treatment site is preferred for tree plantations as it may reduce the cost of pumping (FAO, http://www.fao.org/sustainable-forest-management). Therefore, wastewater-irrigated forestry and agroforestry could also be a potential strategy to dispose urban wastewater and preventing contamination of food chain.

The selection of trees and crops in an agroforestry system depends on the quality and quantity of the wastewater available for irrigation and suitability and tolerance of the crops and trees. Close to the cities, farmers generally prefer a year-round, intensive vegetable system. In wastewater-irrigated system, trees in general are preferred as they act as filters to purify polluted water and mitigate soil or water pollution. Wastewater behaves similar to saline water; therefore, tree and crops selected for agroforestry must be tolerant to salinity, sodicity and waterlogging. The main tree species advocated for degraded lands are *Prosopis chilensis*, *Acacia nilotica*, *Parkinsonia aculeata*, etc. while *Eucalyptus citriodora*, *E. camaldulensis*, *Casuarina equisetifolia*, *Cupressus sempervirens and Khaya senegalensis* for hot and humid climate with fast plant growth.

Selected species should also be easy in propagation, evergreen and fast growing for utilizing higher quantities of wastewater. Trees for the fuelwood purposes with quick biomass production are the best agroforestry system and need to be promoted for wastewater irrigation because of high disposal rates and less risk associated. Promising trees or shrubs for the fuelwood production include *Acacia auriculiformis*, *A. catechu*, *A. mangium*, *A. nilotica*, *Azadirachta indica*, *Grevillea robusta* and *E. camaldulensis*. Management for the silvicultural practices is comparatively easy to practice, and fetch good market price leads to higher income to the farmer.

In drylands with scarce surface water and groundwater resources, treated wastewater can be used to establish and maintain intensive plantations for wood production and environmental, agricultural and social purposes. The technical feasibility of forest tree cultivation using treated wastewater has been demonstrated in various projects and afforestation programmes. Algeria, Egypt, Iran, Jordan, Morocco, Oman, Saudi Arabia, Sudan, Tunisia, the United Arabian Emirates and Yemen, among others, have all developed wastewater reuse programmes to irrigate greenbelts and woodlots or for sand dune fixation. Commonly used species in such programmes are multipurpose and fast-growing trees such as *Eucalyptus*, *Casuarina*, *Acacia*, *Pinus*, *Khaya* (African mahogany) and *Tamarix*.

However, not all tree and crops are suitable for wastewater irrigation, and special care must be taken when planting crops for food production and trees for fruit. In the peri-urban areas of Hubli in Karnataka state of India, the main wastewater-irrigated agroforestry land uses consisted of orchards and agro-silviculture. The two important tree species were sapota (*Achras zapota*) and guava (*Psidium guajava*) along with coconut, mango, areca nut and teak. Species found grown on farm boundaries include neem (*Azadirachta indica*), tamarind (*Tamarindus indica*), *Eucalyptus* spp., poplar (*Populus deltoides*), *Acacia* spp., coconut (*Cocos nucifera*) and teak (*Tectona grandis*). About 20–25% yield advantage has been observed from wastewater irrigation in comparison with tube well water-irrigated fields. Vigorous incidence of insect pests and weeds, early dropping of fruit from trees and deterioration of produce quality were reported to be the main constraint to wastewater-irrigated agroforestry (Bradford et al. 2003).

Due to competition for radiation, nutrients and water, the yields of associated crops could be lower in agroforestry in comparison with sole crops. In an 8-year field rice-wheat-poplar agroforestry system irrigated with sewage, Minhas et al. (2015a) found overall grain yields of wheat and paddy under the agroforestry system averaged 61 and 33% of those under sole crops (Table 8.1). The reduction in crop yields increased with age of poplar trees and became severe after 3 years when the yields of paddy and wheat ranged between 1.1 and 1.4 and 1.7 and 2.4 Mg ha^{-1}, respectively. However, crop irrigated with sewage yielded 12% higher when compared with groundwater. The progressive decrease in crop yields with advancement in tree age was mainly ascribed to the increased canopy and root competition for light, moisture and nutrients. The yield trends showed higher decline rates in both paddy and wheat under agroforestry than their sole crops. These averaged -0.58 and -0.70 Mg ha^{-1} yr^{-1} in paddy with groundwater and sewage irrigation, whereas the corresponding figures for wheat were -0.39 and -0.45 Mg ha^{-1} yr^{-1}, respectively, indicating a higher impact of poplar trees on paddy. The growth and biomass production of poplar trees were almost similar in case of both groundwater and sewage irrigation (Fig. 8.1). Variable doses of nitrogen and phosphorus applied to the understory paddy and wheat crops also had no effect on poplar growth.

There are many valuable cash and subsistence crops that thrive better in the shady climate under trees which enable farmers to diversify and increase their yields while making more efficient use of land. Keeping the high salt and heavy metal contents in wastewater in view, crops selected should also be tolerant to both and accumulate the toxic constituent in plant part which is of least importance or not consumed. In wastewater-irrigated agroforestry system, planting of crops with non-edible economic parts such as cotton should be given priority. Another viable and remunerative option could be the cultivation of crops like cut flowers, aromatic grasses and medicinal plants (Lal et al. 2008, 2008a, 2013). Many of the aromatic and medicinal plants are grown under forest cover and are shade tolerant; agroforestry offers a convenient strategy for promoting their cultivation and conservation (Rao et al.

Table 8.1 Grain yield of crops affected by sewage irrigation and NP fertilizers under agroforestry system during 2001–2008, their trend values (β) and sustainability yield index (σ)

Fertilizer (% of recommended		Paddy during year									Wheat during year									
N	P	2	3	4	5	6	7	Mean	β	σ	2	3	4	5	6	7	8	Mean	β	σ
Groundwater irrigation (GW)																				
25	25	3.1	2.5	1.1	0.8	0.9	0.9	1.5	−0.66	0.17	3.6	3.1	2.5	1.6	1.7	1.8	1.7	2.3	−0.33	0.41
50	50	3.7	3.0	1.3	0.9	1.1	1.1	1.9	−0.64	0.18	4.1	4.1	2.9	2.1	1.9	2.3	2.2	2.8	−0.37	0.46
75	75	4.2	3.2	1.6	0.9	1.2	1.1	2.0	−0.54	0.16	4.5	4.5	3.2	2.5	2.3	2.5	2.3	3.1	−0.414	0.47
100	100	4.5	3.2	1.8	1.0	1.3	1.2	2.2	−0.46	0.17	4.9	4.6	3.2	2.8	2.5	2.4	2.3	3.3	−0.46	0.44
Mean		3.9	3.0	1.4	0.9	1.1	1.1	1.9	−0.58	0.17	4.3	4.1	2.9	2.3	2.1	2.2	2.1	2.9	−0.39	0.45
Sewage irrigation (SW)																				
25	25	4.1	3.2	1.4	1.0	1.2	1.2	2.0	−0.60	0.17	4.3	4.1	3.2	1.8	1.9	2.2	2.0	2.8	−0.44	0.39
50	50	4.5	3.8	1.6	1.3	1.4	1.3	2.3	−0.67	0.19	4.6	4.5	3.5	2.4	2.5	2.5	2.3	3.2	−0.42	0.47
75	75	4.9	3.4	2.4	1.3	1.4	1.6	2.5	−0.68	0.22	4.8	4.8	3.4	2.9	2.8	2.5	2.4	3.4	−0.44	0.49
100	100	5.3	4.2	2.5	1.3	1.5	1.4	2.7	−0.83	0.19	5.1	5.1	4.2	3.1	2.9	2.5	2.4	3.6	−0.52	0.48
Mean		4.7	3.6	1.9	1.2	1.4	1.3	2.4	−0.70	0.19	4.7	4.6	3.6	2.5	2.5	2.4	2.3	3.2	−0.45	0.46
LSD (p = 0.05)																				
WQ		0.4	0.5	0.5	0.2	0.2	0.1				0.9	0.3	0.5	0.4	0.2	0.4	0.3			
Fert.		0.5	0.4	0.7	0.2	0.2	0.3				0.5	0.2	0.7	0.3	0.2	0.3	0.4			
WQ × Fert		NS	NS	NS	NS	NS	NS				NS	NS	NS	NS	NS	NS	NS			

NS = not significant

Fig. 8.1 Growth and yield of poplar under agroforestry system at CSSRI, Karnal, India (Minhas et al. 2015a)

2004). Some of the aromatic plants like *Mentha*, lemon grass (*Cymbopogon flexuosus*), Java citronella (*C. winterianus*), palmarosa (*C. martinii*) and vetiver (*Vetiveria zizanioides*) can be grown intercropped with *Populus deltoides* or *Eucalyptus* spp. for 3–5 years after planting the trees (Singh et al. 1989, 1990, 1998). Some of the tree species having medicinal values which are widely found in agroforestry system in India are given in Table 8.2 (Rao et al. 2004). Tree growth is in general improved mainly due to the inputs given to the intercrops. Teak plantations with patchouli (an essential oil) and cut flowers and foliage (such as anthuriums, heleconias, etc.) have been successfully taken as the overstory/understory mix (Wilkinson and Elevitch 1998). Similarly, some of the legumes like *Medicago rugosa*, *M. polymorpha* and *Trifolium spumosum* have adapted to shaded environments (Mauro et al. 2014). Positive effects of shade on productivity of pasture mixtures with burr medic (*Medicago polymorpha*) and subterranean clovers (*T. yanninicum* and *T. brachycalycinum*) under silvopastoral and vineyard agroforestry systems have been observed recently (Franca et al. 2016; Muscas et al. 2017). At CSSRI, Karnal, India, *Trifolium alexandrinum* (*M. sativa*) and sorghum (*Sorghum bicolor*) were successfully grown under wastewater-irrigated *E. camaldulensis* (Fig. 8.2). However, animals have less liking towards the fodder produced in wastewater-irrigated forestry because of foul smell from droppings of the birds sheltering on the trees.

The benefits of agroforestry include reduced irrigation requirements and therefore, reduced exposure of farmers to wastewater. However, crop restriction does not

Table 8.2 Tree species having medicinal values grown in traditional agroforestry systems in the tropics

Tree species	Agroforestry system	Medicinal use
Acacia nilotica	Field bunds, scattered trees in crop lands, wood lots and grazing lands	Gum used for treating diarrhoea, dysentery, diabetes and sore throat; bark used to arrest external bleeding
Azadirachta indica	Woodlots, scattered trees, shelter belts	Digestive disorders, malaria, fever, haemorrhoids, hepatitis, measles, syphilis, boils, burns, snakebite, rheumatism
Erythrina spp.	Shade tree in coffee, live fence	Different *Erythrina* species have different uses
Prosopis cineraria	Scattered trees in croplands in arid to semi-arid areas	Flowers for blood purification and curing skin diseases. Bark against summer boils, leprosy, dysentery, bronchitis, asthma, leucoderma and piles
Tamarindus indica	Field bunds and scattered trees in croplands in semi-arid regions	Fruit pulp used in Indian medicine as refrigerant, carminative and laxative

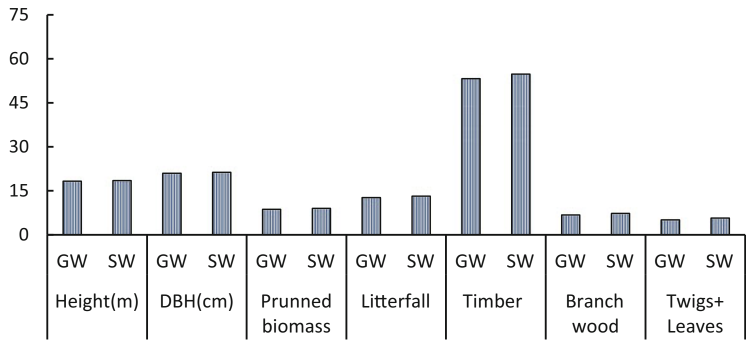

Fig. 8.2 Sorghum and Egyptian clover under wastewater-irrigated *Eucalyptus* plantation at CSSRI, Karnal (Khajanchi Lal, unpublished)

provide protection to farm workers and their families where low-quality effluents are used in irrigation (Blumenthal et al. 2000).

Sewage irrigation may also affect the specific gravity, fibre length and volumetric shrinkage of forest trees. The results indicated that sewage effluent irrigation significantly increased cellulose, lignin, ash and extractive content of wood. Sewage effluent significantly increased wood-specific gravity of chinaberry (Nasser 2008).

8.4.1 Remediation of Urban Effluents

Trees in various agroforestry situations provide bioenergy, biomass, solid wood products and reconstituted products. More intangible opportunities are soil erosion control, uptake of soil nutrients and remediation of agricultural and industrial wastes, carbon sequestration and wildlife habitat (Licht and Isebrands 2005). Use of plants to remove pollutants from environment or to render them harmless is now a day's highly proposed low-cost environment-friendly modern approach. Plants while extracting heavy metals from soil act in association with rhizobacteria and mycorrhizal fungi which solubilize nutrients including heavy metals from minerals. By their extensive growth in the soil, they scavenge a very large volume of soil, and due to high accumulating power, they tremendously increase the uptake of heavy metals by the host plants having mycorrhizal associations. The economic feasibility of tree plantations for biomass and remediation would be definitely more, when they are incorporated into agroforestry system, further enhancing annual income, a critical aspect for acceptance.

Situations where biomass fuel crops offer opportunities for phytoremediation:

1. Where former industrial land has little potential for development and the environmental risks associated are low, biomass fuel crops offer an opportunity to introduce the land into economic use.
2. Where agricultural land has become contaminated through atmospheric depositions or waste material disposal, biomass fuel crops may be grown when food crops are not permitted.
3. Where agricultural land has been contaminated with Cd from rock phosphate fertilizer addition, biomass fuel crops could offer major developments in soil quality within 10–15 years.

Agroforestry systems have also been proven to be able to reclaim polluted land and mitigate soil salinization and acidification (Murthy et al. 2013). For the reuse of land fill leachate, the short-rotation wood crops like willow coppice were found to be cost-effective and alternate to convention methods of on-site leachate treatment in the UK. Leachate irrigation produced statistically higher yields and improved nutritional status of the soil also (Alker et al. 2002). Rockwood et al. (2004) documented that short-rotation woody crops remediate contaminated soil and groundwater across Europe and America. Several tree species have shown their potential for remediation of hydrocarbon, nutrients and heavy metals. Of which, bald cypress (*Taxodium distichum*) and castor bean (*Ricinus communis*) are promising candidate for Cu remediation accumulating as much as 15 mg kg^{-1} in stem. Trees like poplar can effectively remediate the cremated copper arsenate-contaminated sites, and the concentration of arsenic followed the same trend as for nutrients in *Eucalyptus*. Trees could also remediate chlorinated volatile organic compounds from the shallow groundwater through rhizodegradation and fractions of it are taken up in the transpired water through phytovolatilization and phytodegradation (Nzengung et al. 2004).

8.4.2 Wastewater Disposal in Tree Plantations

Wastewater-irrigated agroforestry has long been recognized as a strategy for safe and sustainable disposal of urban effluents and greening the lands which are already contaminated and where food crops are not permitted. In these conditions, wastewater-irrigated forestry and agroforestry bring multiple benefits such as fuel-wood production, environmental sanitation and eco-restoration. Effluent irrigation on tree plantations in Victoria, Australia, commenced in 1973 (Myers et al. 1996). The potential productivity of wastewater-irrigated 14-year-old *Eucalyptus grandis* and *E. saligna* in terms of mean annual increment (MAI) in wood volume was found to be 41 and 31$m^3ha^{-1}y^{-1}$ (Baker 1998; Duncan et al. 1998). Forrester et al. (2010) obtained 56 Mg ha^{-1} above-ground biomass from 5-year-old 1000 *Eucalyptus* trees in Victoria, Australia. In Murray Darling Basin (Australia), area under wastewater-irrigated tree plantations increased from 500 to 1500 ha in >60 variable-size effluent sites (CSIRO 1995). On waterlogged saline soils of Rajasthan, Soni et al. (2012) recorded 77.6 Mg ha^{-1} above-ground biomass of *Eucalyptus* with a stocking density of 1100 trees ha^{-1}. Minhas et al. (2015) observed strong effects of sewage irrigation and stocking density in enhancing growth, water use and timber productivity of *Eucalyptus* plantation. After 3 years, *Eucalyptus* biomass yields were more than twice those of poplar in response to application of sewage effluent, compost and/or mulch in a study at Orlando revealing better performance of *Eucalyptus* in terms of both environmental and economic implications. Trees eefectively increase the amount of effluents that can be applied. *Eucalyptus* may reduce N and P leaching up to 75% when water only is applied and 85% when muluch is added for weed control (Rockwood et al. 2004). Tabari et al. (2011) observed in afforested *Pinus eldarica* (15 years old) stands that municipal effluent-irrigated trees had better growth than irrigated with well water, as indicated by the increased diameter at breast height (DBH), basal area and standing volume of trees.

Plants such as bamboo (*Bambusa arundinacea*), acacia (*Acacia mangium*), neem (*Azadirachta indica*), shishum (*Dalbergia sissoo*), eucalyptus (*Eucalyptus camaldulensis*) and poplar (*Populus deltoides*) have high transpiration rates and, therefore, act as biopump and are effectively utilized for wastewater disposal. Such plants can transpire water several times equivalent to the potential evapotranspiration from the soil matrix alone and reuse wastewater and conserve nutrient energy into biomass. Tree plantations often use water at higher rates than the shorter vegetation because of greater aerodynamic roughness of tree plantations, clothesline effect in tree rows and deeper rooting system for accessing water down to several meters of soil (Rockwood et al. 2004; Thawale et al. 2006; Minhas et al. 2015).

Although water use could be as high as 2500 mm annually in 6-year-old plantation, the exact amount of water and nutrients taken up by *Eucalyptus* depends upon climate and vigour (Annual Report CSSRI 2007; Rockwood et al. 1996, 2004). Water use by tree plantations rarely exceeded 0.5*PAN-E in Australia (Greenwood et al. 1985; Cramer et al. 1999; Morris and Collopy 1999), while values ranging from 0.56 to 1.24*PAN-E in different seasons were reported from India and Pakistan even from the saline sites (Khanzada et al. 1998; Minhas et al. 2015). In a study carried on waterlogged fields, 6-year-old *E. tereticornis* planted in paired rows on the field boundaries at 1 m × 1 m, 1 m × 2 m and 1 m × 3 m spacing transpired 745, 391, 269 ha-mm of water per annum, respectively compared to 1825 ha-mm in case of block plantation with 2 m × 4 m spacing (Dagar et al. 2016). As all the wastewater is utilized in this process, the groundwater pollution problem is minimized. Nutrients present in the wastewater are used by the plants and partly retained in the soil matrix without affecting the soil ecosystem. The system has the following advantages:

- Natural treatment processes and thus termed eco-friendly.
- Development of forests and green belts in urban areas.
- Sink for air pollutants.
- Low-energy and low-cost wastewater treatment system.
- Ease of installation and simplicity of operations.
- Biomass generation and revenue returns.

8.5 Carbon Sequestration in Forestry and Agroforestry Systems

Carbon sequestration (CS) is the process of removing carbon (C) from the atmosphere and depositing it in a reservoir or the transfer of atmospheric CO_2 to secure storage in other long-lived pools. The contribution of the agroforestry system to mitigate the climate change through increased above-ground soil carbon stock is appreciable, and many studies suggested higher amount of sequestration potential of agroforestry system (Dhyani et al. 2009; Sathaye and Ravindranath 1998).

There are two types of carbon sequestration occurring, i.e. one at direct level, where the carbon is converted to carbonates of calcium and magnesium due to inorganic chemical reaction, and the indirect process in which the atmospheric CO_2 is utilized by the leaves to produce photosynthetic pathway compounds, which get stored either in the roots or bole and play an important role as carbon sinks. A considerable part of carbon is again trapped into soil through decomposition process. Different studies show that two-third of carbon is trapped in the underground level, i.e. soil-based mechanisms. Comparing with other systems, the capacity to trap the carbon is in the order of forests > agroforestry > tree plantation > arable crops. The different levels of canopy and plant species in the agroforestry help to trap more carbon than the homogenous crops in the field (Nair et al. 2009).

Forestry and agroforestry systems also provide safer outlet for disposal of urban wastewater because of high transpiration rates. The organic matter and nutrients present in the wastewater fasten the plant growth and also stimulate microbial population which further helps to fasten the trapping process and result in higher C sequestration and other environmental benefits. Compared to groundwater, sewage-irrigated 10-year-old *Eucalyptus* plantation absorbed 7% more total C removed (Minhas et al. 2015). About 61–71% of the total C absorbed (including below ground) and more than 90% of the above-ground C absorption were contributed by the *Eucalyptus* bole, whereas contribution of below-ground biomass ranged between 23 and 33% of the total C stock. The carbon absorption by tree plantations in a given area varies with plantation age corresponding to variations in growth as well as plantation density. Minhas et al. (2015) recorded the annual carbon absorption of 3.5, 12.0, 13.9 and 7.0 Mg ha^{-1} in low (163 stems ha^{-1}), recommended (517 stems ha^{-1}), high (1993 stems ha^{-1}) and very high (6530 stems ha^{-1}) stocking density of 10-year-old *Eucalyptus* plantation, respectively. Fernández-Núñez et al. (2010) also recorded similar observations 11 years after plantation of *P. radiata* on acidic soils of Spain. Total C stocked in 10-year-old sewage-irrigated *Eucalyptus* plantations was 38.6, 121.9, 156.1 and 153.7 Mg ha^{-1} in low, recommended, high and very high stocking density, respectively, whereas 34.6, 114.0, 151.9 and 144.3 Mg ha^{-1} in case of groundwater irrigation. The C sequestered per tree was more in low and recommended stocking density compared with high and very high stocking densities, and the differences increased with age of the trees. Dagar et al. (2016) also found that the total C removed per hectare by 6-year-old *Eucalyptus* planted on farm boundaries at 1 m × 1 m spacing in rice-wheat-*Eucalyptus* agroforestry systems was 1.7 and 2.4 times more than recorded in 1 m × 2 m and 1 m × 3 m spacing which was less than the respective times increase in number of trees per hectare. Wider spacing resulted in better growth of trees due to reduced competition for radiation, root spread and essential plant nutrients, thus higher C absorption per tree. While increasing tree density increases carbon storage, raising densities too high may reduce net absorption due to suppressed tree growth (Naidu et al. 1998). Earlier, Jeet-Ram et al. (2011) also observed 15.5 Mg ha^{-1} carbon in strip plantation of 5 years and 4 months' old plantations. Also the trees efficiently absorb carbon and have mitigating potential to counter the predicted increase in atmospheric carbon concentration (Kurz et al. 2009). Incorporation of tree litter fall in soil also improves soil fertility and C stocks in soil.

Compared to annual crop or pasture systems, agroforestry systems have a higher potential to sequester carbon because of their perceived ability for greater capture and utilization of growth resources (light, nutrients and water). Compared to treeless systems, tree-based agricultural systems store more C in deeper soil layers near the tree than away from the tree. Nair et al. (2010) reported that C stored in agroforestry system ranged from 0.29 to 15.21 Mg ha^{-1} year^{-1} above ground and 30–300 Mg C ha^{-1} up to 1 m depth in the soil. Replacing tree plantation with annual crops aids in carbon emissions and reduces soil organic carbon contents. Wood products can also play a potential role in the mitigation of carbon emissions by substituting more energy-intensive construction materials (e.g. concrete, steel) and fossil fuels (Schlamadinger and Marland 1996).

Land management and soil type also influence C sequestration in agroforestry system. Addition of fertilizers enhances tree growth. In acidic soils of Galicia, Spain, the C sequestered by *P. radiata* (1667 trees ha^{-1}) 11 years after afforestation was increased from 4.09 Mg C ha^{-1} when no fertilizer was applied to 7.0 Mg C ha^{-1} when sewage sludge was used as fertilizer in the same soil (Fernández-Núñez et al. 2010). Mosquera-Losada et al. (2010) also reported that the addition of sewage sludge increased SOM content through the input of organic matter as well as calcium via the sewage sludge. Afforestation is definitely expected to sequester C in above ground, but the impacts of afforestation on soil organic carbon are very diverse ranging from no effect to enrichment or depletion (Fialho and Zinn 2014; Jeet-Ram et al. 2011; Yu and Jia 2015).

8.6 Limitations and Way Forward for Agroforestry

There are many factors that act as substantial barriers to agroforestry. Well-documented barriers include the opportunity cost inherent in locking land away under trees that could be used to generate a more regular income, lack of knowledge about forestry and timber marketing challenges stemming from the dominance of existing major players. Lack of funds is another major issue. Agroforestry has the potential to be a major part of this if the present low returns can be improved. These low returns are primarily caused by a lack of identified tree-based small-scale industries like activated charcoal making from the leftover of agroforestry including seed husks (from tree like *Moringa oleifera*), shells, coconut, etc., which is equally profitable to cropping systems and are able to capture returns for the off-farm environmental benefits they provide. To achieve these objectives, the trees with higher value product per hectare must be located on farms in the form of agroforestry. The scale of reforestation required is significant, possibly involving new plantings to multiply the current forestry estate many times more. In the future, it is well realized that the growth in the tree cover can be mainly achieved through farm forestry particularly in areas of low to medium rainfall and land degradation. Increasing perennial vegetation cover on this scale—whether for timber, biomass or other products—would make a contribution to reducing greenhouse gas emissions, stimulate regional development and provide employment in local processing and manufacturing industries. Biodiversity threats can be tackled using suitable species and designs. Another opportunity could be of mixing the trees with a crop especially suited for remediation instead of agricultural production. A mixture involving a hyper-accumulator understory plant that sequesters contaminant from upper and tree plantations that accumulates the contaminant from deeper layer would increase the efficiency of the system. For arsanic (As) remediation, a potential combination could be a high but nontoxic accumulating poplar clone with the Chinese brake fern (*Pteris vittata*) (Gonzaga et al. 2006; Mecwan et al. 2018).

National standards/quality guidelines need to be prepared for the reuse of treated wastewater for agriculture and forest plantation irrigation, taking into account the legal and regulatory framework (e.g. environmental pollution, water quality, food hygiene and occupational health). Research is needed to produce wood of high calorific value and burning properties. Efforts may be made to study the interactive effects of increased carbon dioxide and water/nutrient deficiency.

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9 Agroforestry Approach for the Rehabilitation of Mine Spoils

A. Raizada and S. K. Dhyani

Abstract

Mining for various types of ores inevitably produces large amounts of waste material that creates severe physical, chemical and biological barriers for the establishment of new plant recruits. In India, mining is carried out in an area of over 0.943 million ha, but the area affected by mining and industrial waste is estimated to be 16.72 million ha. The restoration and rehabilitation of these disturbed areas requires a systematic and scientific approach incorporating diverse aspects relating to microbiology, hydrology, ecology, climate, taxonomy and soil conservation. Planting of trees along with grasses and shrubs accompanied with low-cost soil conservation measures is a proven practice for the rehabilitation of mined-out areas as well as abandoned mines. The use of different indigenous and exotic species for the rehabilitation of different types of mines is briefly described in this chapter along with successful case studies, which can be replicated in similar areas. At the same time, it is necessary that participatory planning for rehabilitation be carried out for rehabilitation measures to sustain over a long period of time; otherwise, all such measures will be short-lived. There is also a need to focus on indigenous species and developing seed banks and nurseries where these resilient species can be raised for planting in the areas selected for rehabilitation.

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Keywords

Biodiversity · Carbon sequestration · Community participation · Ecosystem · Erosion · Mine spoils · Rehabilitation

9.1 Introduction

Mining and mine-related disturbances have altered different types of natural ecosystems leading to forest fragmentation and loss of biodiversity, increased soil erosion, disturbed hydrological cycle and loss of ecosystem services (Chaturvedi et al. 2017). Mining activities in forest areas displace thousands of tribal populations affecting their livelihood. Surface mining permanently alters soil properties, making the process of natural recovery slow and uncertain, whereas altered site edaphic conditions directly influence natural migration, and establishment of recruits of native species and recovery of soil to a 'near' natural state can take about a century. Mining disturbs soil microbial population and growth (Kavamura and Esposito 2010), patterns of natural succession (Singh et al. 2002) and hydrological patterns in the surface and subsurface soils (Sharma et al. 2000; Sheoran et al. 2010).

The primary objective of revegetation of mine spoils is to control erosion and movement of mine debris into streams, road and reservoirs by establishing an effective cover of grasses, shrubs and trees along with suitable mechanical measures in the short term and to assist in the establishment of self-sustaining plant communities by recolonization of native plants in the long term. With recent interest in mitigating global climate change and carbon sequestration, rehabilitation of mine spoils can be potential sites for the sequestration of carbon by increasing carbon pool in soil-plant system. It has been estimated that a reclaimed mine soil can sequester soil organic carbon (SOC) up to 30 Mg C ha^{-1} in 25 years (Akala and Lal 2000).

Long-term mine spoil rehabilitation requires the establishment of stable nutrient cycles which can be initiated by primary colonizers usually among the native species of the region. Development of microbial activities, assisted by moisture conservation practices, and decomposition of plant detritus (fine roots and leaf litter) are the starting points leading to the development of soil organic carbon and nutrients (Roberts et al. 1981). The estimation of soil nutrient dynamics at periodic intervals can play an important role during the restoration process as well as to assess the rate of soil improvement (Mukhopadhyay et al. 2016). While natural colonization can take several decades to occur on mine spoils, the process can be accelerated by planting and seeding of native grasses, shrubs and tree species assisted by generous application of organic and inorganic fertilizers, since the root network of pioneer species can stabilize soil and reduce soil erosion (Maiti and Maiti 2015) while a dense grass cover can support the development of a self-sustaining diverse plant community (Hao et al. 2004).

For the sustainable development of the mined-out area, an ecosystem approach is essential, and instead of a simple revegetation or bio-reclamation, eco-rejuvenation of these areas, based on sound ecological principles, is important (Wali 1987).

Bradshaw (1987) rightly explains this by calling restoration as an 'acid test for ecology'. Restoration literally means 'to bring back into a former or original state' which means that the mined-out areas have to be brought to a state where the 'original' community along with its ecological processes and functions is made fully functional again. In a meta-analysis of 89 restoration projects (Rey Benayas et al. 2009), these workers stress that restoration activities are effective in improving ecosystem services particularly in the tropical regions.

This chapter discusses the use of different indigenous and exotic species for the rehabilitation of different types of mines, rehabilitation practices for mine spoils of major ores in India and carbon sequestration in reclaimed mines. Participatory planning for successful rehabilitation of mined areas has been highlighted.

9.2 Status of Mining in India

India is rich in minerals which are mined over a wide range of ecoregions which in turn have posed a wide range of challenges and difficulties in the process of rehabilitation. In India, mining is carried out in an area of over 0.943 million ha under 7365 mining leases, but the area affected by mining and industrial waste is 16.72 million ha, of which 0.19 million ha is arable land and remaining 16.53 million ha is under open forest (Maji et al. 2010). The list of minerals indicates that 4 fuel minerals, 5 atomic minerals, 10 metallic minerals and 71 non-metallic minerals including minor minerals are mined in India. The value of mineral production is estimated to be worth ₹268,955 crores (US$38.42 billion, at 2018 rates, 1US$ = ₹70).

Mining activities are carried out over the entire country with some states having a large area (Table 9.1) under different types of mines. Closer scrutiny of the data reveals that some of these states have the only remaining natural forest cover and, therefore, require effective rehabilitation activities along with strong legislative

Table 9.1 Area under mining leases in different states of India

Sl. No	Name of state	% of area under mining leases
1	Odisha	20.28
2	Rajasthan	13.90
3	Karnataka	13.16
4	Madhya Pradesh	9.45
5	Andhra Pradesh	7.42
6	Jharkhand	6.96
7	Chhattisgarh	6.76
8	Gujarat	6.52
9	Maharashtra	3.69
10	Telangana	3.23
11	Tamil Nadu	2.76
12	Goa	2.18

Source: Directory of mining leases as of 31 December 2015

Table 9.2 Distribution of mineral belts in India (from Chaturvedi et al. 2014)

Mineral belt	Location	Minerals found
Northeastern Peninsular belt	Chota Nagpur Plateau and the Orissa Plateau covering the states of Jharkhand, West Bengal and Orissa	Coal, iron ore, manganese, mica, bauxite, copper, kyanite, chromite, beryl, apatite, etc.
Central belt	Chhattisgarh, Andhra Pradesh, Madhya Pradesh and Maharashtra	Manganese, bauxite, uranium, limestone, marble, coal, gems, mica, graphite, etc.
Southern belt	Karnataka Plateau and Tamil Nadu	Ferrous minerals and bauxite. Low diversity
South-western belt	Karnataka and Goa	Iron ore, garnet and clay
North-western belt	Rajasthan and Gujarat along the Aravalli Range	Non-ferrous minerals, uranium, mica, beryllium, aquamarine, petroleum, gypsum and emerald

support and participation of local communities who were using these areas for food, fruits, fodder and firewood. Most of the country's mining activities are concentrated in the states of Gujarat, Andhra Pradesh, Jharkhand, Madhya Pradesh, Rajasthan, Karnataka, Odisha, Tamil Nadu, Maharashtra, Chhattisgarh and West Bengal. Together, these 11 states account for 92% of the mines in the country. Most of the major mining districts in India also feature in the list of 150 most backward districts of the country. The area under mining leases (Table 9.1) and the distribution of minerals in the country vary from region to region (Table 9.2) in India.

Almost all of India's minerals are located in regions that also hold most of its native forests, tribal population and major river systems. Forest land has constantly been getting diverted for the purpose of mining and for other developmental projects. The average forest cover of the 50 major mineral-producing districts in the country stands at 28%. During 1980–2005, close to 0.1 million ha of land was diverted across India to make way for 1200 mines. This diversion has destroyed ecosystems as well as livelihoods of people. Most of India's iron ore reserves are along the courses and watersheds of rivers like Indravati, Baitarani, Tungabhadra and Mandovi. Most of the coal reserves of the country are also located within river basins—Damodar, Godavari, Son, Kanhan and Mahanadi-Brahmani.

Mining of minerals leads to two types of damages—one that of the actual area being mined and second the area where the unwanted material is dumped, often unscientifically, which may be 200–300% more than the actual area being excavated for the ore, including area covered for surface transportation (roads) and processing (Soni et al. 1989). In most cases, the ore/overburden ratio is >1, meaning that for every tonne of mineral obtained through opencast mining, an equal and often several times more earth-forming material have to be excavated, and this overburden has then got to be placed in a separate area which also then becomes unproductive. The development of a road network right from the mine head to the processing unit aggravates the problem of soil erosion, dust and sound pollution which directly affects human and livestock population of the area (Valdiya 1988).

Mine spoil properties are directly related to the physical and geochemical properties of the rock strata from which they are derived. Mine wastes, consisting of overburden or mine tailings, consist of stones and rocks and may range between 35 and 65%. The content of coarse particles (>2 mm diameter) in a typical mine spoil varies between <30% and >70% depending on the nature of the rock, techniques adopted to break the rocks and the method of spoil handling (Sheoran et al. 2010). Once the mine spoils are placed on reclaimed surface surfaces and utilized to support plant growth, either with or without topsoil, they are considered to be mine soils (Sencindiver and Ammons 2000), which is essentially a mixture of soil and spoil or overburden that is being managed.

The most significant central legislation has been the Environment Protection Act of 1986, empowering the central government to take all necessary measures to protect and improve the environment. The amendments to the Air Act in 1987 and the Water Act in 1988 empowered the enforcement agencies to close polluting industries and also to stop their power and water supplies. Thus, it is now made clear by legislation that for mining to continue, mine owners need to invest in the rehabilitation of mined-out area and provide all necessary facilities to restore the disturbed ecosystem to some level of sustainability so that natural recovery is hastened. But due to the vast diversity in the climatic and edaphic factors of the mining areas spread all over the country, one single method cannot provide a solution and each mine has to be considered as a separate entity.

9.3 Revegetation Practices for Mined Areas

The ground reality in India and in many developing nations is such that it is practically impossible to revert a land back to its original status, and hence an appropriate word would be ‘rehabilitation’, which means that a degraded land is returned back to its fully functional ecosystem, irrespective of its original state, but in conformity to a prior land use plan. It is also called as ‘partial restoration’ where only selected ecological attributes of the site have been restored. Restoration planning should, therefore, be carefully planned out at an early stage and should as a normal course involve the local community who have been the primary stakeholders (since mining is a temporary activity), and after the mining lease is over and eco-restoration completed, these local communities will be the first users.

Rehabilitation of mined area is an ecological problem, and it is important to incorporate future land use practices while developing the rehabilitation plan. Rehabilitation depends on a factor like type of ore mined, composition of overburden, local climate, topography etc., making the entire process of rehabilitation very site specific. Development of rehabilitation practices and greening of mined-out area have been studied extensively in the developed countries for many years. Research findings, effective legislation and strict penalties have led to well-defined practices that are implemented in most mining operations.

Karr (1968) evaluated Scots pine (*Pinus sylvestris*) for afforestation of oil shale opencast mines. Leguminous species are important colonizers in abandoned mine spoils (Jefferies et al. 1981) and also in rehabilitated bauxite mines (Fox et al. 1982), while Johnson and Bradshaw (1979) have listed 19 perennial legumes which are useful for reclamation. *Amorpha fruticosa* and *Lespedeza bicolour* are two leguminous shrubs which have been tried successfully by Miles et al. (1969) besides 190 grass species, 72 legumes, 20 shrubs, 21 tree species and 9 other plants on different types of strip mine spoils in Pennsylvania (USA).

Leucaena leucocephala as a nitrogen-fixing tree species showed promise on alkaline coal mine spoils in Queensland (Coaldrake and Russell 1978). Norem et al. (1982) evaluated shrub and tree species for planting on copper mine wastes in the USA and determined the performance of species based on slope, aspect and type of mine waste material. Plass (1975) reported that *Betula lanata* and *B. pendula* were more suited for low-pH soils in comparison with *B. lutea*.

Rehabilitation of bauxite residues by using spent mushroom compost (SMC) and gypsum was evaluated in Ireland using *Holcus lanatus*, a perennial grass species (Courtney and Harrington 2012) and which is a common component of Irish semi-natural grasslands. Bauxite residue was amended with varying rates of SMC to increase fertility (0, 60, 80 and 120 Mg ha^{-1}) and gypsum to reduce sodicity (0, 40 and 90 Mg ha^{-1}), and the grass was grown for 1 year. Compost application was essential for sustainable plant growth. Application of compost also increased substrate N, P, K and Mn concentrations, while gypsum application reduced sodicity and improved nutrient uptake for Mn and P.

9.3.1 Rehabilitation Techniques for Mined Areas

Rehabilitation of mines requires careful planning, execution and management since several components are taken care of at the same time—soil amelioration, planting and establishment of suitable species, mulching to prevent soil loss, soil and water conservation measures and protection from stray cattle and other herbivores. In many cases, disturbances from humans also have to be taken care of. In India, the concept of removing and storing topsoil in mine areas and its subsequent use in vegetation establishment, either for pit filling or being laid back over the top surface of mine dumps, is not widely practised due to the high cost involved and is only done by government-run companies. The advantage of spreading a surface soil layer rich in organic matter over the overburden is that this layer facilitates the rapid establishment of planted seedlings and germination of grass seeds or other propagules already available in the soil. In the coal mines of the USA, the federal Surface Mining Control and Reclamation Act of 1977 requires regrading of the mine spoil to approximate pre-mining land contour, replacing the topsoil and establishing a vegetative cover by the mine operator prior to the release of reclamation bond. While increasing the cost, an important impact of these laws and acts was the successful establishment of the vegetation on the reclaimed mine land.

The differences between graded and ungraded (where no topsoil has been spread out) are given in Table 9.3. As is evident from the table, graded mines have an artificially created 'environment' in which grasses and legumes can establish rapidly

Table 9.3 Differences between graded and ungraded mines for rehabilitation practices

Parameter	Graded mines	Ungraded mines
Topsoil	Topsoil stored before mining is applied on the spoils to an average depth of 25–30 cm	No topsoil applied separately on the spoil
Land use	Mostly forests	Mostly pasture and hay land
Soil structure	Presence of granular to subgranular structure after 10–15 years of reclamation. Coarse fragments at depths >30 cm	Even distribution of coarse fragments and signs of soil development after 20 years of reclamation
Compaction	High	Low
Aeration	Very low in the upper layers and therefore anaerobic conditions may prevail in the subsoil below 30 cm depth	As the spoil is evenly distributed, aeration is high and homogenous
Macropores	Only in depths > 30 cm	Throughout the soil profile
Infiltration rate	Low	High
pH	Mostly neutral to alkaline and sometimes acidic	Mostly acidic
Nutrient availability	Moderate	Low
Biomass productivity	Low in the early years of reclamation but productivity may be high after 15–20 years	Consistently low
SOC	Overall sequestration high	Overall sequestration low

Source: Holl and Cairns (1994), Skousen et al. (1994)

provided they are planted in time and match the site climatic conditions. Akala and Lal (1999) reported the advantages of graded and ungraded coal mines from Ohio. The SOC pool for 0–30 cm depth for the undisturbed control sites was 56.6 Mg C ha^{-1} for forest and 66.3 Mg C ha^{-1} for pasture. In comparison, the SOC pool in the forest and pasture of graded mine land for 0–30 cm depth after 25 years of reclamation was 58.9 Mg C ha^{-1} and 62.7 Mg C ha^{-1}, respectively. In ungraded mine land, the SOC pool in the 0–30 cm depth after 30 years of reclamation was 51.5 Mg C ha^{-1} in forest and 58.9 Mg C ha^{-1} in the pasture.

Once the area for rehabilitation has been decided, it is necessary that some basic conservation measures are taken up to stabilize the unstable slopes, reduce erosion and allow runoff water to move slowly out of the area. Low-cost soil and water conservation measures are the first line of defence after which biological measures are taken up. Retention of soil and hence moisture availability improve the chances of seedling establishment in the degraded site. Selection of plant species (grasses, shrubs or trees) should be carefully chosen based on their known capacity to withstand harsh environments (hot dry summers, frost and often summer fires), rapid establishment and biomass accumulation.

Planting activities, therefore, have to be planned at least 1 year in advance so that seedlings are procured and planted at the right time and establishment is successful. A mixture of nitrogen-fixing tree species, non-nitrogen-fixing trees, grasses and shrubs should be preferred with early pioneer species mixed together. In extreme cases, where there is very little soil or climatic conditions are adverse, it is advisable to take up sodding of native grasses which establish quickly, have a high soil binding capacity and create ambient environments in the rhizosphere which assists build-up of soil microbial biomass.

9.4 Rehabilitation Practices for Major Mine Spoils in India

Several studies have been carried out in India exploring the reclamation of gypsum mines, dolomite (Prasad 1989), iron ore (Raizada et al. 2002), lignite mines, coal mine spoils (Prasad and Shukla 1985) and rock phosphate mines (Soni et al. 1989) and limestone mines in the north-western Himalayas (Raizada and Juyal 2012). A brief account of various rehabilitation studies in different mining areas is discussed as follows:

9.4.1 Rehabilitation of Iron Ore Mines

India is the fourth largest iron ore-producing country in the world, and more than 95% of deposits are concentrated in the states of Odisha, Karnataka, Chhattisgarh, Jharkhand and Goa. In Odisha, Joda and Koira are two of the most prolific ore-producing regions spread across Keonjhar and Sundargarh districts. The state produced nearly 70 million tonnes of ore in 2015–2016. Karnataka has the largest high-quality iron ore reserves in India, estimated to be 2269 million tonnes of haematite. Chhattisgarh has 18% of the country's iron ore reserve with major deposits being in Bastar and Durg districts, both of which are tribal populated area with dense forest cover. Jharkhand has a quarter of India's iron ore deposits, and the Chiria mine has the largest iron ore deposit in the world, estimated to be of about 2000 million tonnes. Goa is India's top iron ore exporting state although the ore is low grade with only 55–58% iron content.

The erstwhile Kudremukh Iron Ore Mining Company (KIOCL) situated in the Western Ghats, a biodiversity hotspot, which was closed down under Supreme Court's orders in December 2005, took massive afforestation programs to green the area devastated by unscientific mining and planted large number of seedlings of *Eucalyptus* and *Acacia*, *Casuarina equisetifolia*, *Acrocarpus fraxinifolius* and *Dalbergia sissoo*.

Manivanan et al. (2016) reported the activities taken up to rehabilitate overburden of iron ore mines in Goa. They reported that fruit tree species are suitable for the mines, given the climatic conditions of Goa, with abundant rainfall and sunshine. They suggested that biological reclamation through establishment of horticultural crops in iron ore overburden is an environmentally sustainable option. Soil

Table 9.4 Height increments over 8 years after planting of various fruit species in iron ore overburden with different pit filling mixtures (Manivanan et al. 2016)

Species	T1—lateritic soil		T2– FYM		T3—press mud		T4—control	
	First year	Eighth year	First year	Eighth year	First year	Eighth year	First year	Eigth year
Tamarindus indica	47	395	49	440	49	380	34	342
Azadirachta indica	92	510	47	495	47	472	42	420
Mangifera indica	115	400	80	360	65	290	62	253
Garcinia indica	50	220	57	250	52	198	51	189
Syzygium cuminii	64	390	64	450	64	370	61	350
Artocarpus heterophyllus	41	395	63	410	40	350	36	310
Anacardium occidentale	59	460	48	485	61	410	42	345
Emblica officinalis	71	565	73	525	112	410	68	340

amendment and excavation of staggered contour trenches are essentially required while planting horticultural crops in magniferrous clay iron ore over burdens. Cashew (*Anacardium occidentale*), mango (*Mangifera indica*), gooseberry (*Emblica officinalis*), jackfruit (*Artocarpus* spp.), *jamun* (*Syzygium cuminii*), *kokum* (*Garcinia indica*), *neem* (*Azadirachta indica*) and tamarind (*Tamarindus indica*) were evaluated with three types of soil amendments in the planting pits, namely, mixing overburden with (a) laterite soil, (b) farmyard manure and (c) press mud.

Out of eight species evaluated, cashew, gooseberry, mango and *jamun* outperformed the other species in terms of growth and canopy establishment compared to jackfruit, *kokum*, *neem* and tamarind. The performance of gooseberry was the best with laterite soil amendment with mine overburden soils. Cashew, mango and jamun performed better with farmyard manure amendment with mine overburden (Table 9.4).

Stylo (*Stylosanthes hamata*), a fodder legume, was the best cover crop for rehabilitation of iron ore overburdens as compared to *Mucuna hirsutus*. The excavation of staggered contour trenches and broadcasting of seeds of stylo as cover crop reduced soil erosion by 86% over control sites (Fig. 9.1). *Stylosanthes hamata* and litter generated from horticultural plants could marginally increase soil nutrient contents in the iron ore overburden. Cashew, mango, gooseberry and jamun are possible horticultural crops for biological reclamation of iron ore overburden. Preparing pit filling mixture either with laterite soil or farmyard manure in the ratio of 1:1 is recommended as soil amendment for planting horticultural crops in iron ore overburden. Staggered contour trenches with the dimensions of

Fig. 9.1 A fully rehabilitated iron ore overburden with grass and tree cover near Goa, India

Fig. 9.2 View of an iron ore overburden with freshly planted seedlings (left) and the same site 10 years after protection (right)

2 m × 0.5 m × 0.5 m at 4 m vertical interval are recommended for controlling soil erosion.

In mines operated by a private concern—Sesa Sterlite at Sankhali iron ore mines in Goa—rehabilitation measures included the laying of geotextile mats over newly dumped overburden to stabilize the surface material, and sodding of grass slips was carried out. Further, seedlings of cashew nut, gooseberry, kokum, bamboo (*Dendrocalamus strictus*), *Alstonia scholaris*, *Acacia mangium* and *Casuarina equisetifolia* were carried out. After 10 years (Fig. 9.2), the area has been completely rehabilitated, and enumeration of vegetation 10 years after rehabilitation indicated the occurrence of 612 genera and 716 species of various plant life forms.

In the semi-arid tracts of Karnataka, rehabilitation of iron ore burden was reported by Adhikari et al. (1998). A partially abandoned iron ore mine situated in the Metrici Reserve Forest Area, 30 km south-west of Bellary, was selected for rehabilitation. An area of about 80 ha was treated during 1990–1996. The region is hot and dry for a major part of the year, and annual precipitation is about 470 mm, mostly received through receding monsoons. The entire forest area of 116 ha drains into a large reservoir 3 km downstream where it serves as a source of irrigation and drinking water for several small hamlets occupied by poor tribal people (*Lambani*) who are basically herdsmen. Due to high sediment load and release of toxic material from the overburden washing, the water of reservoir had turned red in colour and was unfit for use.

After an initial survey of the entire area, demarcation of areas with very coarse material where only engineering measures could be implemented was marked out, followed by demarcation of areas where bioengineering (mechanical with agroforestry interventions) measures could be taken up and finally by demarcation of areas where only vegetative (agroforestry interventions) measures would be sufficient. Since the iron ore waste material and soil are heavy (particle density, 4.45–5.20 g $cc^{-1)}$, the material moves down the slopes as more and more overburden is dumped at the higher levels. This material ultimately settles down in streams and on hill slopes burying native vegetation permanently. With every high-intensity storm (four to six in a year), this overburden moves down the slopes, destroying more and more area. The movement of the overburden can be controlled by combination of temporary and semi-permanent structures.

The use of low-cost soil conservation measures (crib structures and brushwood check dams) on mild slopes (<10% slope) was carried out, while on slopes ranging from 10 to 20%, gabions were erected with length's ranging from 6 to 10 m and horizontal interval (HI) of 20 m. On slopes and drains ranging from 20 to 50%, gabions were erected with lengths varying from 2 to 6 m depending on site characteristics and HI of 5 to 10 m. Further, on slopes <10%, continuous contour trenches of 0.45 m width and 0.45 m depth were excavated with tractor-drawn rippers. Within these trenches, 1-year-old seedlings of *Acacia auriculiformis*, *Cassia siamea* and *Eucalyptus* hybrid were planted. Survival of seedlings in these trenches was about 80% with *C. siamea* developing with widest canopy of 3.5 m in nearly 5 years. Seedlings were planted 4 m apart within the trench. Three-year-old seedlings of *Eucalyptus* hybrid were planted in continuous contour trenches. In the bed of *nalas* (small water channels), seedlings of *Albizia amara* and *Carissa carandas* were planted which showed satisfactory survival. Planting of suckers of *Agave americana* was carried out in the approach paths for the planted area and along the boundary to prevent entry of stray cattle. This was an effective, low-cost method to prevent damage to seedlings. Pit planting of assorted species in the upper reaches was undertaken. Over a period of six years, stability was provided to the unstable hill slopes which reduced debris movement from 212 Mg ha^{-1} $year^{-1}$ to 14 Mg ha^{-1} $year^{-1}$. Significantly clean water moved in the numerous streams whenever there was runoff-causing rainfall. Prevention of biotic disturbances allowed vegetation to establish and grow in the middle and lower reaches.

9.4.2 Rehabilitation of Coal Mines

India has the fifth largest coal reserves in the world and is the fourth largest producer of coal in the world, producing 662.79 million metric tonnes in 2016–2017. As of 31 March 2017, India had 315.14 billion metric tonnes of the resource. The estimated total reserves of lignite coal as of 31 March 2017 were 44.70 billion metric tonnes. Due to high demand and poor average quality, India is forced to import high-quality coal to meet the requirements of steel plants. The energy derived from coal in India is about twice that of the energy derived from oil, whereas worldwide, energy derived from coal is about 30% less than energy derived from oil.

Direct seeding for rehabilitation of mine spoils is sometimes carried out because it is easier and cost-effective, although subsequent to germination a lot of aftercare is required, including protection from herbivores. Usually a mixture of native grasses and fast-growing tree species is used for coverage of a mined area (Singh et al. 1995). In a study carried out by Jha et al. (2000) in coal mine spoils at Singrauli, it was reported that in flat areas, rapid height increment was observed in *Leucaena leucocephala* and slower growth was observed in case of early colonizing species like *Acacia catechu*, *Acacia nilotica* and *Azadirachta indica*; however, on slopes, *A. indica* was the fastest-growing species followed by *L. leucocephala*, *Terminalia arjuna*, *Pongamia pinnata* and *A. catechu*. They also reported that the presence of grasses and forbs also encouraged the establishment of migratory species like *Butea monosperma* and *Melia azedarach*.

The performance of *Dendrocalamus strictus*, a multipurpose bamboo, in the rehabilitation of a coal mine spoil in Jatany coal mine in the Singrauli region was reported by Singh and Singh (1999). They reported an annual recruitment which varied from 18% (third to fourth year) to 36% (fourth to fifth year) while mortality rate was only 6–7%. These plantations accumulated sufficient biomass (Table 9.5) which is more than other species. This bamboo species is also efficient in rapidly increasing microbial biomass, indicating its potential for rehabilitation purposes.

Sharma et al. (2004) reported, upon the rehabilitation of lignite mines in the hot dry state of Rajasthan, the site receiving a total of 265 mm of rainfall annually in

Table 9.5 Oven-dry stand biomass of bamboo plantation at different ages on coal mine spoil at Singrauli (Singh and Singh 1999)

	Biomass (t ha^{-1})		
Components	Three-year-old*	Four-year-old*	Five-year-old*
Foliage	6.1^{a}	7.9^{a}	10.7^{b}
Current shoot stem	4.5^{a}	3.7^{a}	5.4^{a}
Old shoot stem	15.3^{a}	19.6^{a}	26.4^{b}
Dead shoot stem	4.5^{a}	5.3^{a}	6.7^{a}
Rhizome	11.9^{a}	14.0^{a}	18.8^{b}
Root	3.6^{a}	4.1^{a}	5.3^{b}
Total	46.9^{a}	55.8^{a}	74.7^{b}

*Values in a row superscripted with different letters are significantly different from each other at $p < 0.05$

Table 9.6 Species used for planting in lignite mines in Barmer region of Rajasthan, India, for rehabilitation (Sharma et al. 2004)

Species	Leguminous	Non-leguminous	Exotic
Tree	*Prosopis cineraria* *Pithecellobium dulce*	*Azadirachta indica* *Salvadora persica* *Tamarix aphylla* *Tecomella undulata*	*Colophospermum mopane*
Shrubs		*Ziziphus nummularia* *Capparis decidua* *Dichrostachys nutans*	*Acacia nubica*
Grasses		*Cenchrus ciliaris* *Cymbopogon jwarancusa*	

12–33 rainy days. They used a combination of various methods for the rehabilitation procedure. They backfilled the abandoned pits with a heterogeneous mixture of bentonitic clays, shale and leonardite (weathered lignite) and covered this with a layer of fresh topsoil 0.25–0.30 m thick. The area was then planted with a combination of species (Table 9.6) with different treatments consisting of microcatchment rainwater harvesting, soil amendment in pits and plant establishment methodologies.

Damage by frost was highest (88%) in *T. aphylla* and least in *D. nutans* (2%), while species like *P. cineraria*, *C. decidua* and *Z. nummularia* showed no damage due to frost. Micro-water harvesting measures led to increase in different species with significant ($p < 0.01$) increase in height in case of *A. indica* (471%), *S. persica* (267%), *C. mopane* (180%) and *T. aphylla* (132%) and least in case of *P. dulce* (31%). Changes in collar girth between 1997 and 2000 in the plants grown with micro-water harvesting structure were significant ($p < 0.01$) in case of *A. indica* (700%), followed by *S. persica* (567%), *P. cineraria* (300%) and *C. mopane* (275%) which are more than the control sites where increase was only 112–140%. Notably after a period of 4 years, establishment of annual species was observed which is a natural process in vegetation succession. In this study, the choice of species was based on their use as top feed species for herbivores and grasses for fodder and slope stabilization. It was expected that rural communities of the adjoining areas would provide protection to the newly created fodder resources from the rehabilitated mines.

In a study reported by Prasad and Dhuria (1989) from iron ore mines in Durg (Madhya Pradesh), a number of leguminous and non-leguminous species were planted for rehabilitation purposes. After 4 years, the most successful species in terms of biomass accumulation was *L. leucocephala*, followed by *A. lebbeck* and *Eucalyptus* hybrid (Table 9.7), which indicates that nitrogen-fixing trees establish and grow rapidly in the region and also enrich the site in terms of build-up of SOC.

In coal mines of West Bengal, species like *Albizia lebbeck*, *Anacardium occidentale*, *D. sissoo*, *Delonix regia*, *Gmelina arborea*, *Madhuca latifolia*, *Syzygium cuminii* and *Shorea robusta* and shrubs like *Ziziphus mauritiana* and *Dodonaea viscosa* have been used successfully.

Table 9.7 Biomass productivity of selected species raised on iron ore mined-out sites in Madhya Pradesh (Prasad and Dhuria 1989)

Species	No. of trees ha^{-1}	Total tree weight (kg per tree)	Total dry weight (Mg ha^{-1})
Albizia lebbeck	1630	15.58	25.40
Albizia procera	1600	4.14	6.62
Acacia auriculiformis	1700	4.63	7.88
Dalbergia sissoo	624	4.80	3.00
Eucalyptus hybrid	1370	12.46	17.07
Pongamia pinnata	1420	5.85	8.31
Leucaena leucocephala	1716	19.00	32.60
Prosopis juliflora	355	7.24	4.01

Table 9.8 Growth of seedlings planted on dolomite overburden in Madhya Pradesh (Source: Prasad and Chadhal 1987)

Species	Average height (m)	Average girth at breast height (cm)
Acacia campalycantha	7.85	26
Eucalyptus hybrid	7.73	28
Acacia auriculiformis	6.60	21
Gmelina arborea	5.55	25
Pongamia pinnata	2.25	13
Albizia procera	0.53	22

Measured 5 years after planting

9.4.3 Rehabilitation of Dolomite Mines

Dolomite is a common mineral found in a wide variety of rocks. As a mineral, dolomite is used in agriculture, where its ability to neutralize acid makes it a key ingredient in specialty fertilizer and as a soil conditioner. Dolomite is used as a source of magnesia (MgO), a feed additive for livestock, a flux in metal processing industry and an ingredient in the production of glass, bricks and ceramics. Dolomite is extracted from nearly 179 mines, with Chhattisgarh alone producing 28% of the total production (2012–2013) followed by Andhra Pradesh (23%), Odisha (13%) and Karnataka and Madhya Pradesh (9% each).

Rehabilitation of these mines using different species was reported by Prasad and Chadhal (1987). The performance (in terms of height) in decreasing order was of *Acacia campalycantha* > *Eucalyptus* hybrid > *Acacia auriculiformis* (Table 9.8), while in terms of girth increment, *Eucalyptus* hybrid was the best.

9.4.4 Rehabilitation of Limestone Mines

The lower Himalayan region adjoining the Doon Valley is rich in limestone, and extensive mining was carried out from hundreds of mines until the Supreme Court-enforced ban in 1985 stopped all mining activities in the region. Since limestone deposits are fractured and fragmentary by nature, mining results in the production of fine wastes resulting in the accumulation of fine waste material, which often moves downhill slopes and causes siltation and pollution of water resources and damage to forest cover and infrastructure. Implementation of bioengineering measures and planting of trees and shrubs were carried out in the limestone mines for rehabilitation purposes (Dhyani et al. 1988; Juyal et al. 1998). These measures also led to forest recovery (Table 9.9; Raizada and Samra 2000) and appearance of late colonizers in the rehabilitated areas. Some of the species were planted in contour trenches and some in pits filled with soil and FYM, and the performance of *Acacia catechu*, *Bauhinia retusa*, *D. sissoo* and *Salix* was successful.

A subsequent estimation of the recovery levels (Raizada and Juyal 2012) indicated that there were a large number of species in the pole stage followed by tree and sapling stage. Tree associations indicating successful regeneration patterns in the lower, middle and upper reaches were *L. leucocephala* and *A. catechu*; *A. catechu* and *Boehmeria rugulosa*; and *A. catechu* and *Woodfordia exserta*, respectively. At the rock phosphate mines in Mussoorie hills, Soni et al. (1990a,b) reported that indigenous species had a higher survival rate than exotics, and the species evaluated were *A. catechu*, *D. sissoo*, *Salix* sp., *Pinus roxburghii*, *Robinia pseudoacacia*, *Populus* sp., etc.

At the limestone quarries in Durg district of Chhattisgarh, Prasad (1989) evaluated different species like *D. sissoo*, *P. pinnata*, *A. auriculiformis*, *E. officinalis* and bamboo which were planted in 45 cm^3 pits filled with 2.5 kg of FYM. They reported that most of the species performed well except bamboo.

Table 9.9 Diversity indices for two locations in a rehabilitated limestone mine at Sahastradhara in the Doon Valley (Raizada and Samra 2000)

	Site I—Disturbed forest adjoining the limestone mine		Site II—Rehabilitated mine		
Diversity index	Trees	Shrubs	Trees	Shrubs	Grasses
No. of species	9	6	13	11	5
Richness	0.943	0.60	2.221	2.222	0.868
Conc. of dominance	0.266	0.326	0.318	0.200	0.436
Diversity (H)	1.668	1.267	1.511	1.880	1.014
Abundant species	5	3	4	6	2
Very abundant species	3	3	3	4	2
Equitability (J)	0.76	0.70	0.58	0.78	0.63

9.4.5 Rehabilitation of Chromite Mines

Odisha accounts for 98% of the total chromite (chromium ore) sources of the country of which 97% occurs in the Sukinda valley (200 km^2) in the Jaipur district. Chromite is used in the domestic market for production of iron-chromium alloys (ferroalloys), and some chromite is used for refractories, ceramics and preparation of chromium-containing chemicals. For rehabilitating these mines, both exotic and native species have been used. Among the successful species include *Acacia auriculiformis*, *A. nilotica*, *Cassia siamea*, *Eucalyptus tereticornis*, *Simarouba glauca*, *Anacardium occidentale*, *L. leucocephala*, *Bauhinia variegata* and *D. sissoo*.

9.4.6 Rehabilitation of Bauxite Mines

The total reserves of bauxite in India is estimated to be of about 2500 million tonnes which is just 1% of the world's total reserves, and more than half of the reserves are in Odisha and Andhra Pradesh. Other states which also have this ore are Jharkhand, Madhya Pradesh, Gujarat, Maharashtra and Karnataka. Some of the important species which have been used for rehabilitation purposes are *Acacia auriculiformis*, *Eucalyptus camaldulensis*, *Grevillea robusta*, *Grevillea pteridifolia*, *Emblica officinalis*, *Pongamia pinnata*, *Melia azedarach*, *Albizia procera* and *Dendrocalamus strictus*.

9.4.7 Rehabilitation of Zinc Mines

The state of Rajasthan is the largest producer of zinc in India (88.6% of total production), followed by production from Andhra Pradesh (3.31%), Madhya Pradesh (2.16%) and some from Bihar and Maharashtra. Prior to mining in the zinc mines of Rajasthan, the forests were covered mainly with *Anogeissus pendula* (Dhokra)-dominated vegetation. The other species in the forests were *Acacia leucophloea* (Aranja), *Acacia catechu* (Khair), *Holoptelea integrifolia* (Chural), *Butea monosperma* (Palas) and *Ziziphus mauritiana* (Ber), etc. However, extensive mining destroyed the native vegetation, and some efforts for rehabilitation have been undertaken by planting native grasses like *Dichanthium annulatum*, *Cenchrus ciliaris* and *Paspalidium geminatum* with a fair degree of success. Planting of 1-year-old seedlings of trees *A. pendula*, *A. catechu* and *H. integrifolia* has also been undertaken which have shown good performance showing potentials of good silvopasture system.

9.4.8 Rehabilitation of Manganese Mine Spoil Dumps

Reclamation has been carried out using press mud and bio-fertilizers in pits of tree plantations. Species like *Tectona grandis*, *Gmelina arborea*, *Azadirachta indica* and

Dalbergia sissoo have been observed to be the most successful in quick establishment and growth (Juwarker et al. 1984).

9.5 Service Functions of Agroforestry Systems in Mine Area Rehabilitation

The formal study and promotion of agroforestry systems (AFS) for land management began at the end of the 1970s (Steppler and Nair 1987) with the initial focus being on the biological and socio-economic advantages. By the end of the 1990s, increased concern about environmental issues led to attention on the environmental service functions of alternative land uses. It was recognized that AFS have many inherent advantages over monocultures and that AFS provide many environmental services (carbon sequestration, nutrient cycling, protection of microbes and increase in microbial biomass, in situ soil and water conservation) besides increase in aesthetic value in terms of increasing green cover in wastelands and degraded habitats like mined-out areas and mine spoils.

Soil amelioration by AFS has been reviewed by Young (1989) and Buresh and Tian (1998). Soil improvement in AFS is linked to the growth of nitrogen-fixing trees or deep-rooted trees and shrubs that increase nitrogen availability through biological nitrogen fixation, recycle of plant nutrients and build-up soil organic matter (Rao et al. 1998). Planting trees on fallows is a potential solution to improve soil fertility in areas of reduced fallow cycles in slash and burn agriculture usually carried out by many tribal communities in East and Central India. Nitrogen availability, determined by inorganic soil nitrogen or aerobic nitrogen mineralization in the 0–20 cm soil depth, can be significantly higher after a rotation of N-fixing trees in comparison with other tree species. Szott and Palm (1996) reported that in comparison with leguminous herbaceous fallows, leguminous tree fallows increased the total phosphorus, potassium, calcium and magnesium stocks in the biomass, litter and exchangeable cations in the 0–45 cm soil profile.

As is normally observed in dense forest areas, AFS can also reduce soil erosion by producing a cover of litter and by applying pruning-mulching which cover the soil, reduce the impact of raindrops, improve soil structure, increase soil nitrogen content and also enhance nutrient retention. Beer et al. (1998) reported these benefits from coffee and cacao plantations in Costa Rica. Raizada et al. (2002) investigated the nutrient dynamics of plantations of six species (aged between 9 and 23 years) which had been raised on stony flood plains in the north-western Himalayas. They reported that re-translocation of nutrients varied between evergreens and deciduous species, with maximum N being re-translocated in *Morus alba* (84%) and least in bamboo (16%). Fractional annual turnover rate varied between elements and species (six species were studied), with N having the highest values (68–92%) and magnesium the least (13–62%), although the impact of these plantations on soil physico-chemical properties was not significant in the 0–7.5 cm layer.

The potential of AFS in securing water supplies has not been studied in detail, but it is certain that AFS influence water cycling by increasing water retention in soil,

Table 9.10 Impact of rehabilitation measures undertaken in a limestone mine at Sahastradhara, Dehradun, Uttarakhand, India

Particulars	Before treatment (1983)	After treatment (1996)
Debris outflow (Mg ha^{-1} $year^{-1}$)	550	8
Monsoon runoff (%)	57	37
Lean period flow (days)	60	240
Vegetation cover (%)	10	80

Source: Annual Reports IISWC, Dehradun

Table 9.11 Water quality parameters (in ppm) for treated and untreated limestone mine at Sahastradhara, Dehradun, Uttarakhand, India

Site	Calcium	Magnesium	Sulphates
Treated mine	74	34	138
Untreated mine	188	39	240
Water-quality standards	75	50	250

Source: Annual Reports IISWC, Dehradun

Table 9.12 Changes in mine spoil characteristics of the treated mined area at Sahastradhara, Dehradun, Uttarakhand, India

Soil characteristics	1985	1991	1997
pH (1:2.5)	8.1	7.9	7.5
Organic C (%)	0.13	0.18	0.42
Total N (%)	0.01	0.01	0.05
$CaCO_3$ (%)	54.6	34.6	31.0
Bulk density (Mg m^{-3})	1.63	1.53	1.47

Average of 14 sampling points; Source: Annual Reports IISWC, Dehradun

reducing runoff and increasing infiltration. Moreover, trees in AFS can cycle nutrients in a conservative manner preventing their losses through nutrient leaching. As a result of less runoff and leaching, micro-watersheds (<200 ha) with adequate forest cover or AFS covering a large portion of the soil surface yield clean water for more number of days. Investigations on a treated limestone mine at Sahastradhara (Dehradun) indicated that the effect of rehabilitation measures undertaken led to significant changes in patterns of runoff and led to water availability much beyond the monsoon season (Table 9.10); water quality also improved with significant reduction in the calcium, magnesium sulphate and bicarbonate content (Table 9.11). After 14 years of agroforestry measures and other low-cost rehabilitation technologies, the pH of the mine spoil came down from 8.1 to 7.5, and organic carbon increased from 0.13 to 0.42%, whereas $CaCO_3$ content decreased from 54.6 to 31.0%, and bulk density decreased from 1.63 to 1.47 Mg m^{-3} which showed that planting of MPTS, shrubs and grasses helped in improvement of soil characteristics over a period of time (Table 9.12).

9.5.1 Carbon Sequestration in Tree Plantations on Reclaimed Mines

The effects of plant biomass on soil organic carbon build-up in mine soils have been investigated by several workers. Nyamadzawo et al. (2007) reported, on the basis of their studies carried out in a number of reclaimed mine soils of different ages in Northeast Ohio (USA), that reclamation of disturbed coal mine soils increased the soil C concentration and C stocks and that reclamation by first seeding with grasses followed by planting of trees was the best option for quick accretion of soil C and improvement of soil quality (pH, bulk density, total N and C). Silvopastoral systems can play an important role in carbon sequestration in soils and in the woody biomass (above and below ground), with the amount of carbon fixed being affected by tree and shrub density, their spatial distribution, distribution of roots and fine root turnover rates. In high-density plantations raised on stony flood plains in the NW Himalayas, Raizada et al. (2014) reported that C sequestration rates ranged from 1.32 to 0.55 Mg ha^{-1} $year^{-1}$, and the trend among the tree plantations was *Dalbergia sissoo* > *Bauhinia variegata* > *Grewia optiva*.

In recent years, there has been growing interest on the carbon sequestration potential of reclaimed mines. Tripathi et al. (2014) reported from a 19-year-old afforested stand on coal mine spoil that, in the 0–30 cm soil profile, the C stock (Mg C ha^{-1}) was 22.9 with an annual C accumulation rate of 1.20 Mg C ha^{-1} $year^{-1}$. In a study from Jharia coalfields in Jharkhand, India, Das and Maiti (2016) calculated, using allometric equations for *Albizia lebbeck*, *Dalbergia sissoo* and *Bambusa arundinacea*, the carbon (C) stock and soil organic C in 4-year-old plantations, understorey vegetation and litter and compared the same with forest site. Total C stock in tree plantations of the reclaimed site was estimated to be 30.3 Mg C ha^{-1}. The study concluded that (1) coal C is responsible for overestimation of C stock in reclaimed mine soil, (2) maximum C stock is stored in aboveground biomass component and (3) reclaimed mined lands can take approximately 17 years to reach the level of C stock of reference forest site in dry tropical climate.

Ahirwal and Maiti (2017) estimated the C sequestration of revegetated coal mine dumps in Jharkhand, India. Mine soil quality was assessed in terms of accretion of soil organic carbon (SOC), available nitrogen (N) and soil CO_2 flux along with the age of revegetation. After 14 years of revegetation, SOC and N concentrations increased three- and fivefold, respectively, and were found equivalent to the reference site. Accretion of SOC was estimated to be 1.9 Mg C ha^{-1} $year^{-1}$. Total ecosystem C sequestered after 2–14 years of revegetation increased from 8 Mg C ha^{-1} to 90 Mg C ha^{-1} with an average rate of 6.4 Mg C ha^{-1} $year^{-1}$. Aboveground biomass contributed maximum C sequestration (about 50%) in revegetated site. CO_2 flux increased with age of revegetation and was found to be 11, 33 and 42 Mg CO_2 ha^{-1} $year^{-1}$ in younger, intermediate and older dumps, respectively. Soil respiration rate in the revegetated site was more and influenced more by temperature than soil moisture. This study also showed that tree species like *Dalbergia sissoo* and *Heterophragma adenophyllum* may be preferred for revegetation of mine-degraded sites.

9.6 Participation of Local Communities in Rehabilitation Projects

Activities taken up for rehabilitation of mines require a certain level of planning and execution, based on site climatic conditions, soil and geological factors, slope, aspect and finally meeting the demand of the end user. Most often the mining activities in the developing countries result in the displacement and resettlement of rural and tribal populations in new areas where they are not able to adjust themselves and long to go back to their traditional way of life. In many instances, there have been violent protests against the transfer of forest lands for mining activities and the displacement of traditional dwellers, especially in the states of Odisha, Jharkhand and Chhattisgarh where there is scope for expansion of mining activities but at the cost of removal of forest cover.

Conventional rehabilitation practices to restore mine areas end up with tree planting programs and some ill-conceived activities for harvesting of runoff water and very little investments in soil-stabilizing measures, creation of basic infrastructural facilities for affected populations including all weather roads. Afforestation activities consist of planting exotic species like *Eucalyptus*, *Cassia siamea*, *Acacia auriculiformis*, *Pinus* sp., *Cupressus torulosa*, etc. that have very little multiple use except as firewood. As a result of that, the affected population who reside near or in the disturbed forest area have no affinity or sense of belonging to the newly planted 'forest', and over time these rehabilitated areas are destroyed by illicit grazing (of annual grasses), harvesting of trees in the 'pole' stage for use as firewood and general degradation of the restored area. In an interesting article by Datar et al. (2011) in which the authors catalogued species used in 37 studies dealing with post-mine land rehabilitation, it was revealed that only four species—*Pongamia pinnata*, *Dalbergia sissoo*, *Albizia lebbeck* and *Azadirachta indica*—had the highest frequency of reporting. This is indicative about the need for using the vast number of species used by rural communities in their daily life for rehabilitation projects so that they develop affinity and interest in protecting the rehabilitated areas. Some species of ethnobotanical importance, out of a large number of potential species, which need to be raised for planting out in rehabilitation areas, are listed here in Table 9.13. These species find uses in traditional folklore, medicines and minor products for daily use in the states of Odisha, Chhattisgarh, Jharkhand and Madhya Pradesh. It is expected that planting of seedlings that are of multiple use and acceptable by rural communities will allow the willing participation of the population in the development of long-lasting forest cover in rehabilitated areas.

It is, therefore, necessary that these displaced communities be involved in the planning process for rehabilitation, and species choice must nearly match their demands so that participatory decision-making wins over their confidence and species selected are those that they have traditionally been using for ages in their normal life. Some of these species also lead to income-generating activities like bamboo basket making from bamboo species, wooden toys from *Boswellia serrata*, agricultural tools from other species and musical instruments and drums from species like *Gmelina arborea*, *Caryota urens*, *Pterocarpus marsupium* and

Table 9.13 Plant species used by tribal and rural communities in different regions of India

Plant species/ family	Uses
Azadirachta indica Meliaceae	• Leaves used for curing insect bites, removing dandruff, ear ailments, skin disorders, increasing immunity • Flowers are used for removing intestinal worms and reducing nausea • Twigs are used as toothbrush and for maintaining alkaline levels of saliva and preventing plaque formation • Wood is used to handcraft hair combs Neem oil is used extensively in the cosmetic industry, for soap and handwash and as mosquito repellent
Bauhinia malabarica Caesalpiniaceae	• Young shoots of this species are edible and are prescribed to treat cough, gout, glandular swellings and goitre, leprosy, urinary disorders and wounds • While the leaves are extensively used as fodder, the wood is used for making charcoal and houses • Bark is a source of tannins which are used for dyeing
Calotropis gigantea Asclepiadaceae	• The bark and roots are used in preparing medicine for the treatment of diarrhoea, constipation and stomach ulcers and also for toothache and joint pains
Celastrus paniculatus Celastraceae	It is actually a climbing shrub and its seeds have medicinal value. Used in the Ayurveda system of medicine for the promotion of memory and learning abilities
Costus speciosus Zingiberaceae	• Perennial shrub with bright red flowers • Used in the Ayurveda system of medicine in the treatment of disturbances in lipid metabolism like obesity and hyperlipidaemia. It is also considered useful in the management of diabetes
Helicteres isora Malvaceae	• Called as the Indian screw tree due to its twisted fruit pods • The root juice and fruits are topically applied to cure snake bite. Fruit pods are highly nutritive. The fruit powder mixed with some other herbs and spices is given to new mothers in order to cope with post-delivery weakness • The roots and the bark are used as an expectorant, demulcent, constipating and lactifuge and useful in colic, scabies, diabetes, diarrhoea and dysentery
Manilkara hexandra Sapotaceae	• A slow-growing but fairly large evergreen species. The tree typically is 12–25 m tall and 1–3 m in trunk circumference. The bark is greyish and rough • Wood is hard, durable and heavy; it is used for heavy structural work, gate posts and big beams and also is used for turning and carpentry • Ripe fruits are eaten in Bastar (MP) while Bhils of Jhabua (MP) boil the stem bark with water and take bath with this water to cure body ache
Premna latifolia Verbenaceae	• Wood is scented, light brown, grained and moderately hard, used for making frames • Leaves are diuretic, used as medicine • Tender shoots and leaves are used for making curries and fodder. In Odisha, the leaves are cooked as vegetable and the wood is used for extracting fibre
Semecarpus anacardium Anacardiaceae	• Also called as marking nut, it was used by washer men to mark cloth and clothing before washing, as it imparted a water-insoluble mark to the cloth • Seeds are eaten in Bastar (MP), and fruits are roasted and eaten
Sterculia urens Sterculiaceae	• Also called as Indian tragacanth or gum *karaya*; a natural gum known as *gum karaya* is exuded by the tree when the bark is damaged

(continued)

Table 9.13 (continued)

Plant species/ family	Uses
	• Karaya gum swells when it absorbs water and is used as a laxative because it adds bulk to the contents of the intestine. Karaya gum is also reputed to have aphrodisiacal properties • The seeds are roasted and eaten • In Bastar (MP), the fruits are pounded and the seeds are separated and cooked as a vegetable • Wood is used for making toys and also as firewood
Tragia involucrata Euphorbiaceae	• The Indian stinging nettle is a slender, twining herb with stinging hairs • Tribes in Odisha use its roots as an antidote for snake bite. The root is made into a paste with mustard oil and given orally. Also applied locally • Leaf and root are used for curing blood dysentery

Lagerstroemia parviflora. However, this also means that it is necessary to develop forest nurseries for raising seedlings of indigenous species for eventual planting out in areas selected for mine rehabilitation. In order to do this, state forest departments need to identify areas where young seed-producing trees are abundantly available, fine-tune their seed collection programs and raise at least 1-year-old seedlings for planting.

9.7 Conclusion

Mining impacts the natural landscape and discharges large volumes of wastes that pose serious environmental pollution problems to the environment, to human health as well as to agriculture. Ecological restoration of mining areas is a multidisciplinary approach involving experts from mining, geology, surveying, ecology, environment and land use planning. Reclamation and regeneration of mining areas in India are highlighted with emphasis on appropriate plant species for mine spoils and tree plantations to improve soil properties, plant biomass production and carbon sequestration. Restorations of limestone quarries in Dehradun, iron ore overburden in Kerala and coal mining areas of Singrauli are successful cases of large-scale post-mining restoration practices in India. However, the pace of post-mining landscape restoration research and practice in India is slow. Therefore, it is important to mainstream the restoration of mining-degraded lands in national research strategies; the inventory of the number, area and current status of abandoned mining lands; the compiling of information on plant species that can be used for the rehabilitation of mining spoils; and the development of suitable models of agroforestry systems for the rehabilitation of mining areas. While technology for restoration and rehabilitation is available, it is necessary to involve local communities in the development and subsequent management of the restored areas, supported with the enforcement of environmental laws and rehabilitation guidelines.

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10 The Role of Tree Plantations in Improving Soil Fertility and Carbon Sequestration on Coal Mine Spoils

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Abstract

Surface coal mining results in the degradation of habitat, altering soil properties, including its biological, physical and chemical features. This review explains the harmful effects of coal mining, such as increased soil erosion, nutrient leaching, increase in soil bulk density, accumulation of heavy metals in soils, and decline in soil pH, organic matter, plant available nutrients, cation exchange capacity (CEC), and microbial activity. Revegetation through tree plantations is one of the efficient methods of restoring fertility of soil by improving the organic matter content and its various properties, increasing plant available nutrients and CEC, and enhancing biological activities. Some promising tree species that could be used for revegetating coal mine spoils in India are, viz., *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria*. These tree species are acid-tolerant, suitable for growing in infertile soil, and are able to add substantial quantity of organic matter to the soil. From this review, it may be concluded that the revegetation of coal mine spoil through tree plantations can improve fertility of soil and can support the establishment of vegetation; however, the process of restoration of the vegetation, close to the original level, may take longer time, depending on the extent of degradation.

Keywords

Coal mine spoil · Habitat degradation · Tree plantations · Restoration · Soil organic matter

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10.1 Introduction

Among the important processes linked with the economic development of a country, surface mining has been considered very significant. However, surface mining results in degradation of the habitat, altering soil properties, including its biological, physical, and chemical features (Sheoran et al. 2010; Macdonald et al. 2015). Due to unfavorable soil conditions for the growth of plants, the process of natural recovery of such altered systems generally becomes a time taking process, and could be considered very similar to the primary succession on the natural habitats (Ahirwal et al. 2016). The process of mining removes plant covers, alters soil structure by excavation, disturbs the microbial communities, transforms landforms, and damages the surface and subsurface hydrological cycle (Sheoran et al. 2010; Shrestha and Lal 2011). When favorable soil nutrients are removed, the original soil properties are disrupted in the process. In the open cast mining of coal, large amount of nutrient poor overburden soil material is piled on the surface of the nearby land, which creates a serious problem for the rehabilitation of such kind of highly disturbed ecosystem (Ahirwal and Maiti 2018). In the overburden dumps, the bioavailability of metals increases, proportion of sand in soil becomes higher, moisture declines, bulk density increases, and the soil organic matter relatively decreases (Sheoran et al. 2010), leading to the formation of adverse conditions for revegetation (Chaturvedi and Singh 2017).

In naturally colonized sites, the overall plant biomass may increase with age of reclamation; however, the variations could also be due to species composition and density of trees present at a specific site (Fig. 10.1). Coal mine spoils are deficient in

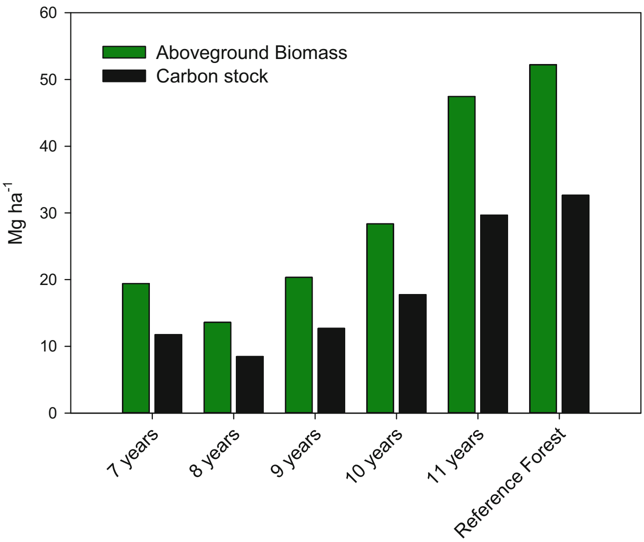

Fig. 10.1 Tree aboveground biomass and total tree carbon stock of the reclaimed chronosequence sites (naturally colonized) and the native forest site. Adapted from Ahirwal et al. (2017)

major physical, chemical, and biological properties of normal soils, however upon revegetation, the changes in soil characteristics and accumulation of nutrients during the regrowth of ecosystem could be detected in the form of changes in the level of biomass and diversity of plant species (Bradshaw 1983). There could be various ways for the evaluation of successful reclamation; however, changes in soil properties are the most important signals for restoring the ecosystems.

Although the natural restoration of coal mine spoil is a slow process, it can be enhanced by plantations of important trees and herbaceous species. This mechanism of two-tiered vegetation establishment increases the biodiversity and soil fertility of coal mine spoil (Dutta and Agarwal 2002). Often, for mitigating the problem of deficiency in soil nutrients, various kinds of fertilizers have also been suggested. Several studies have highlighted the increment in biomass and productivity of important herbaceous species as a result of fertilization (e.g., Piha et al. 1995 and Singh et al. 1996). However, few studies have also indicated that fertilization has variable impact on the development of woody species which are planted on mined landscape (Vogel 1981).

According to Singh et al. (2002), plantations can play a significant role in the revegetation of coal mine spoils. On the sites which are severely degraded, plantations of suitable species have shown remarkable catalytic effects on the successional growth of native forest than on the unplanted sites (Parrotta and Knowles 2001; Chaturvedi and Singh 2017). Since all plants exhibit different rates of growth, they also differ in their capacity of stabilization and nutrient enrichment. Generally, the trees and shrubs are considered to provide a permanent cover of vegetation on coal mine sites with very little aftercare. Several trees have been reported to exhibit a capacity to maintain or increase the organic matter content of soil, enhance the nitrogen-fixing capacity, minimize the rate of erosion, and improve the physicochemical and biological properties of soil (Jha and Singh 1991; Frouz et al. 2009). However, it has been suggested that the impact of trees on nutrient content of soil will depend mainly on their nutrient cycling features, for example, the chemical composition of litter and decomposition rate (Byard et al. 1996). Since all tree species do not possess equal capacity of growing in a harsh environment of coal mines, selection of suitable tree species that can resist a wide fluctuation in climatic conditions, for example, severe drought, high temperature, and poor soil nutrient conditions, has been considered significant for restoration effort (Ahirwal et al. 2017). Moreover, the tree species that possess the capacity to grow under low-nutrient conditions and exhibit high biomass accumulation capacity are considered more suitable for revegetation of coal mine spoil (Singh et al. 2006; Mukhopadhyay et al. 2013, 2014).

10.2 Characteristics of Tree Plantations

Trees have been considered to be very efficient, as compared to other plants in supplementing large amount of organic matter to aboveground and belowground vegetation and to the soil layer (Chaturvedi et al. 2011; Chaturvedi et al. 2012;

Chaturvedi and Raghubanshi 2015; Chaturvedi et al. 2017a, b; Singh and Chaturvedi 2018). The deep roots of trees could cover a greater soil depth in the revegetating coal mine compared to the grasses, and can easily penetrate to the comparatively soft spoil layers, which are beneath the "cap" of hard trapped clays (Mensah 2015). Generally, the rooting depth for herbaceous species is around 50 cm, while for trees, it is around 3 m; although, there are certain *phreatophytes* growing in coal mines which may tap into groundwater and have been found to reach the soil depths up to 15 m, particularly in arid climates (Mensah 2015).

Trees perform various ecosystem functions and can sufficiently improve soil properties through different processes, such as maintenance or improvement of soil organic matter content, nitrogen fixation through biological processes, nutrient uptake from aboveground to belowground soil layers and transfer to roots of understory herbaceous flora, maximizing water infiltration and accumulation, reducing the loss of nutrients due to erosion and leaching, improvement of soil physical characteristics and of biological activities of soil, and reduction in soil acidity. Trees have also been found to create new self-sustaining top soils, while the plant litter and exudates from roots enhance the nutrient cycling in soil (Padmavathiamma and Li 2007; Mertens et al. 2007; Mensah 2015; Singh and Chaturvedi 2018).

Moreover, revegetating coal mine spoils with suitable trees could reduce the tendency of soil for compaction (Chaturvedi and Singh 2017). Trees could increase the drainage of rainwater in the vegetated mine spoil, compared to the new soil; therefore, less amount of water remains at the upper soil surface, which minimizes the possibility of soil erosion (Mensah 2015). Also, the efficiency of trees in absorbing nutrients released by weathering of rocks is more compared to the herbaceous species (Young 1989).

The investigation of spatial patterns of distribution of plants on the afforested land of restored mine spoils could provide important information which may be utilized to test the restoration measures applied for the revegetation (Moreno-de las Heras et al. 2008). Zhao et al. (2012) described the processes and patterns of spatial distribution of afforested plants and suggested that these investigations are important for checking whether or not the applied reclamation measures are sufficiently able to produce sustainable communities of plants and to what extent they are providing theoretical evidence for the improvement of ecological recovery techniques. Further, Zhao et al. (2015) studied the changes in structure of population and size class, and the patterns of spatial distribution of the two dominant species, *Robinia pseudoacacia* (ROPS) and *Pinus tabuliformis* (PITA), in the mixed forests after 17 consecutive years in the opencast coal mine spoil of Pingshuo located in Shuozhou City, northern Shanxi Province, northwestern China, and suggested relevant basic information important for ecological research and implementation of the projects for vegetation restoration in the opencast coal mines.

10.2.1 Monoculture Vs Mixed-Species Plantations

Single-species plantation in the initial stage of revegetation in coal mine spoil is generally not recommended, since in the marginal environment, single species will get very little or no maintenance; hence, the success of that species becomes unpredictable (Morgan 2005). Also, the monocultures are disadvantaged because of its vulnerability to being attacked by harmful pests and outbreak of diseases. Compared to mixed plantations, the single-species plantations cannot satisfactorily be utilized for multiple purposes and other conservation roles; such plantations are not able to provide a balanced ecosystem service and also are not able to produce a balanced and stable system in the context of changes in environmental conditions and other directional changes (Mensah 2015). Furthermore, the mixed plantations are more resistant to variations in climatic conditions; they could form a more stable ecosystem and can sequester carbon in a more sustainable way.

The mixed-species plantations commonly contain woody species, including bushes and trees, together with grasses and forbs. As reported by Young (1989), for controlling soil erosion, the tree canopy cover is less effective compared to those of ground-layer flora. In a study conducted for 10 years, Liao et al. (2000) observed that the total litter produced by the mixed plantation of *Cunninghamia lanceolata* and *Michelia macclurei* (both in the proportion of 1:1) was 43% greater compared to that of the monoculture of *C. lanceolata*. In another similar study, Parrotta (1999) reported that litter production was comparatively greater for mixed plantations compared to the monospecific *Eucalyptus* plantations located in Puerto Rico. In an earlier study, Zhang et al. (1993) observed that the annual litter production of a 55-year-old mixed plantations of *Pinus massoniana* and *M. macclurei* was 11.2% greater compared to that of an equal aged *P. massoniana* monoculture stand. Moreover, several studies have reported that the species composition is considerably important for the quantity of litter production at different regions within the same climate range (Yang et al. 2004; Mensah 2015).

For the maintenance and conservation of soil fertility in the forest ecosystems, nutrient released from the litter decomposition plays a significant role (Singh and Chaturvedi 2018). Wang et al. (1997) reported that the quantity of nutrient return via decomposition of leaf litter to forest floor recorded in the mixed plantation of *C. lanceolata* and *M. macclurei* was around two and three times greater compared to that in the pure culture of *C. lanceolata*. Besides, the study of Forrester et al. (2005) also reported that the mixed plantations of *Acacia mearnsii* and *Eucalyptus globulus* elevated the quantity as well as rates of nitrogen and phosphorus cycling through the aboveground litterfall as compared with the pure culture of *E. globulus*.

10.2.2 Exotic Vs Native Species Plantations

For the reclamation of coal mine spoil, tree species needs to be carefully selected because the newly introduced species could also become pests in some situations. The tree species selected for revegetation should be checked carefully so that it could not become a problematic weed for the local or regional habitat. If any exotic tree is introduced for plantation, priority should be given to those species which exhibit better adaptation to the local environment. For plantation in a new developing habitat, native or indigenous species are generally preferred to exotics also because they are mostly expected to adjust into the fully functional ecosystem and also they are climatically adapted to the habitat (Singh et al. 2004a; Chaney et al. 2007; Li et al. 2015).

The revegetation plan for coal mine spoils should be focused toward the natural succession of the plant communities. In most of the cases, the objective of reclamation is to establish pioneer species so that the mine spoil could be covered and soil be improved in short time period, allowing native species to establish and become abundant as the colonizing pioneer plants decline (Morgan 2005). Singh et al. (2004a) suggested that for revegetating coal mine spoil, native species should be given preference. If we measure the plant diversity of the neighboring sites, we could get better information about the species which are most suitable for surviving in that habitat (Morgan 2005). Chaturvedi and Singh (2017) reported that the soil fertility of the revegetating coal mine spoil improve much faster when planted with native leguminous species compared to the native nonleguminous species. Moreover, the native leguminous species are more efficient in modifying soil properties compared to exotic leguminous species in the short time period (Sheoran et al. 2010). However, if the site condition is very severe, the use of foreign or exotic plant species could not be ruled out, particularly when the local environment has degraded drastically or where very few local species are found (Mensah 2015).

On the coal mine spoils, nitrogen has been observed to be a major limiting soil nutrient, and regular application of nitrogen in the form of fertilizers may be required for maintaining healthy growth and development of the vegetation (Song et al. 2004). A more convenient and alternative approach could be the introduction of leguminous trees and other nitrogen-fixing species. Studies in coal mine spoils have reported that the nitrogen-fixing leguminous species have a remarkable effect on the fertility of soil because legumes produce readily decomposable and nutrient-rich litter and they have high turnover of fine roots as well as nodules (Singh et al. 2002, 2004b; Tripathi et al. 2014). Also, the mineralization of nitrogen-rich litter from leguminous species substantially transfers nutrients to companion species, subsequently increasing the nitrogen cycling, leading to the development of a self-sustaining healthy ecosystem (Zhang et al. 2001).

10.3 Effect of Tree Plantations on Soil Properties

10.3.1 Physical Properties

The comparative evaluations of the physicochemical properties of the soils by Chaturvedi and Singh (2017) for natural forest, deforested land, and mine spoils at different stages of natural recovery are given in Table 10.1. Among the important soil properties, soil organic carbon contents for the natural forest and deforested land

Table 10.1 Soil properties of the mine spoils and the native forest and deforested land

Soil properties	Forest soil	Deforested soil	5-year-old spoil	10-year-old spoil	12-year-old spoil	16-year-old spoil	20-year-old spoil
Root biomass (g m^{-2})	–	–	284	342	537	485	553
pH	6.4	7.3	7.7	7.9	8.1	8.1	7.9
Water holding capacity (%)	52	46	52	45	46	48	50
Gravimetric soil water (%)	8.6	2.9	4.6	2.9	4.2	2.6	5.4
Mineral nitrogen (N) (μg g^{-1})	16.4	14.8	5.8	7.6	7.9	9.9	15.6
Total organic carbon (C) (μg g^{-1})	867	422	209	276	356	360	496
Total N (μg g^{-1})	75	40	20	23	28	32	36
Total phosphorus (P) (μg g^{-1})	29	15	7	10	12	13	16
C/N	11.6	10.6	10.5	12	12.7	11.3	13.8
Microbial biomass N (%)	4.3	4.7	4.8	4.2	3.9	4.4	3.6
Microbial biomass P (%)	1.7	1.8	1.7	1.8	1.7	1.8	1.6

Adapted from Chaturvedi and Singh (2017)

area were 3.01 and 1.98%, respectively. The total nitrogen in the 5-year-old spoil was only 23% of that in the native forest soil. Microbial carbon (C), nitrogen (N), and phosphorus (P) in the soil varied from 209 to 867 μg C g^{-1}, from 20 to 75 μg N g^{-1}, and from 7 to 29 μg P g^{-1} soil, respectively. The recorded values were maximum in the natural forest soil and minimum in the 5-year-old spoil (Table 10.1). Microbial biomass carbon, nitrogen, and phosphorus were around four times higher in the natural forest soil compared to the 5-year-old spoil.

Under natural forest cover, the soil structure is of superior quality, porosity and moisture conditions are favorable for plant growth, and the soil is resistant to erosion, while these soil properties remarkably decline after forest clearance (Singh and Chaturvedi 2018). Porosity is the most important physical property of the soil; pores with diameter ranging from 5 to 50 μm determine the water holding capacity of soil, while the pore size over 250 μm diameter are required for the penetration of roots (Young 1989).

Tree plantations favor the development of ground vegetation such as herbs and shrubs by improving soil conditions. Consequently, the established ground vegetation protects the soil from erosion by the impact of raindrops and runoff, and they also trap sediments moving with rainwater. Trees and shrubs also increase the strength of the top-layer soil through their large root network. Due to the influence of vegetation cover, infiltration of rainwater into the soil has been observed to increase (Morgan 2005). According to Young (1997), the decline in runoff to some degree occurs by canopy interception as well as direct transpiration; however, the major part of decline in runoff is caused by greater soil infiltration capacity under the tree cover. Hamilton and Pearce (1987) also highlighted that the large network of surface root system under tree plantations serves to increase infiltration as well as hold the soil, thus reducing erosion.

The distribution of soil particle size is a critical soil physical factor in determining a successful revegetation on overburden dumps in coal mines as it affects water holding capacity, bulk density, and the availability of soil moisture as well as nutrients (Sheoran et al. 2010). Jha and Singh (1991) reported that the soil textures of coal mine spoils are heavily disturbed as a result of irregular pilling of materials on overburden dumps. An investigation by Dutta and Agarwal (2002) shows that tree plantations in a coal mine spoil exhibit significant variations in silt and clay contents, which indicates that plantations are able to change the soil texture in due course, after their growth and establishment.

The vegetation cover also acts as buffer and controls the rapid change in soil temperature. The bare soil of coal mine spoil absorbs heat from the sun and in a very short time becomes very hot during summer season and very cold during winter; however, when the soil is covered by vegetation, it is insulated from the direct heat of the sun, and therefore, it becomes neither very hot nor very cold (Kolay 2000).

10.3.2 Chemical Properties

Tree plantations tend to decrease the acidity of soil through addition of alkaline substances to the soil surface after litter decomposition (Singh et al. 2002). However, whether the litter from the selected tree plantation could significantly increase the pH of acidic soils is not very certain, since it depends on the selected tree species and the quantity of litterfall (Singh et al. 2004b; Mukhopadhyay et al. 2013). The soil pH increment due to tree plantations indicates that the organic matter input from the planted trees modifies the pH of the soil of coal mine spoil. Since majority of the plant species selected for revegetation are generally dicotyledonous, they release more base cations such as Ca^{2+} into the soil, leading to increase in the pH of the soil of revegetated coal mine spoil, compared to the fresh mine spoil (Dutta and Agrawal 2003).

The atmospheric nitrogen is absorbed by the nitrogen-fixing organisms and stored in the soil. This nitrogen is then taken up by plants in the form of nitrates. Fixation of nitrogen in soil is commonly done by leguminous species which contain root nodules to achieve this function. In coal mine spoil, leguminous trees such as *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria* are more effective. The atmospheric nitrogen absorbed by the leguminous trees in turn contributes to improving the fertility of soil. Moreover, the litterfall elevates the organic matter content of the soil which ultimately provides a suitable soil environment for the fixation of atmospheric nitrogen (Banning et al. 2011; Chaturvedi and Singh 2017). The protein concentration in this organic matter, together with the protein contents of soil microorganisms which decompose into amino acids and later oxidize to nitrates, is absorbed by plants (Singh and Chaturvedi 2018). According to Franco and de Faria (1997), the legume tree species used for plantation could contribute about 12 tons of dry litter biomass and 190 kg of N/ha/yr. for renovation of the degraded soils.

The soils fertilized with organic matter also contain higher mineralized phosphorus. Mbagwu et al. (1994) observed that the soils treated with higher rates of organic matter exhibited remarkable increase in phosphorus content. It has also been reported that the surface litter contributes only small percentage of the total phosphorus accumulated in the forest (Ren and Yu 2008). Moreover, Ren and Yu (2008) reported that the deficiency of phosphorus is the inhibitive factor leading to slow growth of *Acacia mangium* plantation.

10.3.3 Biological Properties

Organic matter content of soil is the portion of soil that includes animal as well as plant remains occurring at various stages of decay (Singh and Chaturvedi 2018). The soil organic matter, according to Plaster (2009), is commonly composed of three components: (1) living biota (plant roots, microbial organisms, and various other organisms which occupy the soil), (2) fragments of plants as well as animal remains present at various stages of decay (fallen leaves, dead and decomposed organisms, animal excreta, and crop residues), and (3) residues of active decay and several organic compounds present in the soil which is commonly called humus.

On coal mine spoils the increased litter supply from aboveground and belowground plant residue during establishment of vegetation is generally responsible for the elevation of organic matter content in soil and improvement of the soil productivity (Singh et al. 2002). In a study by Kumar et al. (2018), the soil organic carbon pools (particulate organic carbon, non-particulate organic carbon, and total organic carbon) were observed to increase with the age of reclaimed mine spoil (Fig. 10.2); however, the carbon/nitrogen ratio was reported higher in young dumps, compared to the intermediate and old dumps (Fig. 10.2). The study by Kumar et al. (2018) also exhibited that even after 26 years of reclamation, the carbon pools of the coal mine spoil do not reach to the level of natural forests, although the quantity of total nitrogen and microbial biomass carbon was very similar in both habitats (Fig. 10.3).

Although tree plantations improve soil fertility in various ways, the maintenance of soil organic matter levels by supplementing litter and root residues has been considered as the major factor for soil fertility improvements. It has been reported that the approximate chemical composition of organic matter in soil is 50% carbon, 5% nitrogen, 0.5% phosphorus, 39% oxygen, and 3% hydrogen (Barber 1995). However, these values may vary from soil to soil in different habitats. In a typical well-drained mineral soil, the organic matter content is low and varies from 1 to 6%

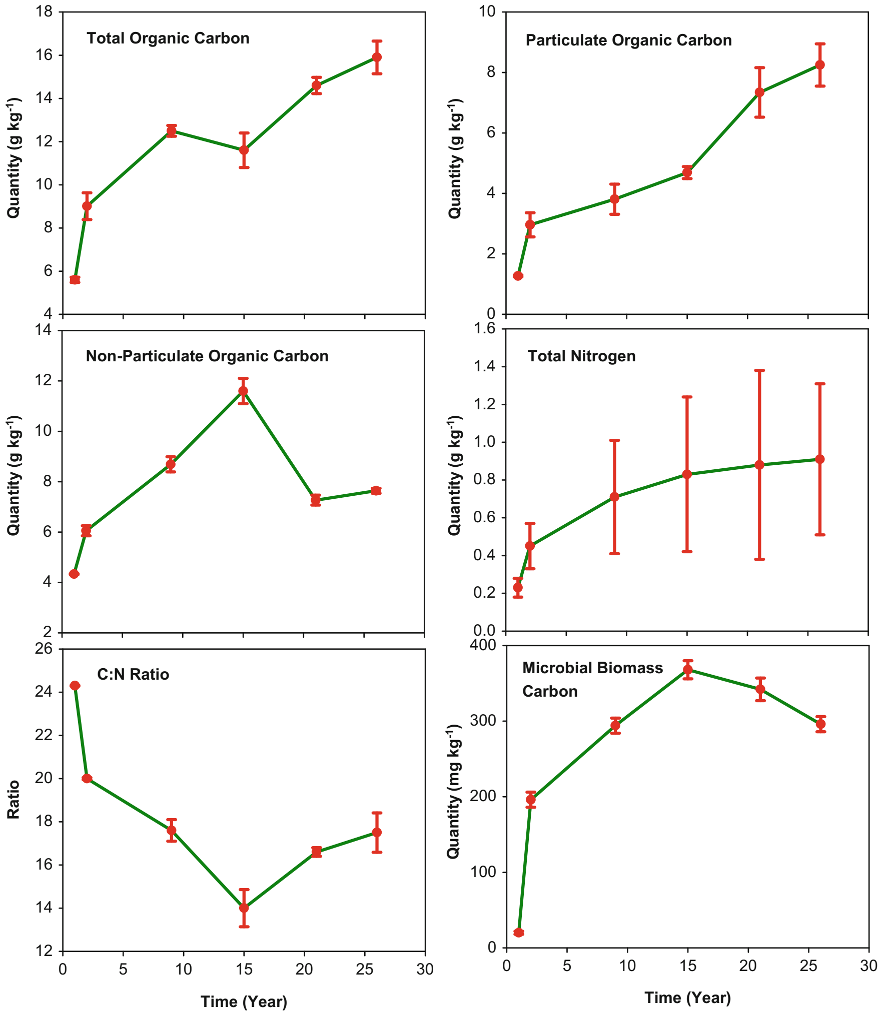

Fig. 10.2 Soil organic carbon pools of the reclaimed chronosequence coal mine sites. Mean ± standard deviation (SD) ($n = 6$). Adapted from Kumar et al. (2018)

by dry weight in the top-layer soil, and the value is even less in the down layer, subsoil (Barber 1995).

The organic matter in soil improves conditions of all types of mineral soils for several reasons. In sandy soils, organic matter helps in increasing the capacity of soils for holding water and nutrients. For clay soils, organic matter makes loosen up the clay particles and improves their tilth (Plaster 2009). The important function of organic matter has been noticed during the supply of nutrients where the organic matter blocks the phosphorus fixation sites, which increases the phosphorus availability to plants. It has been reported that a good organic matter level in soil provides

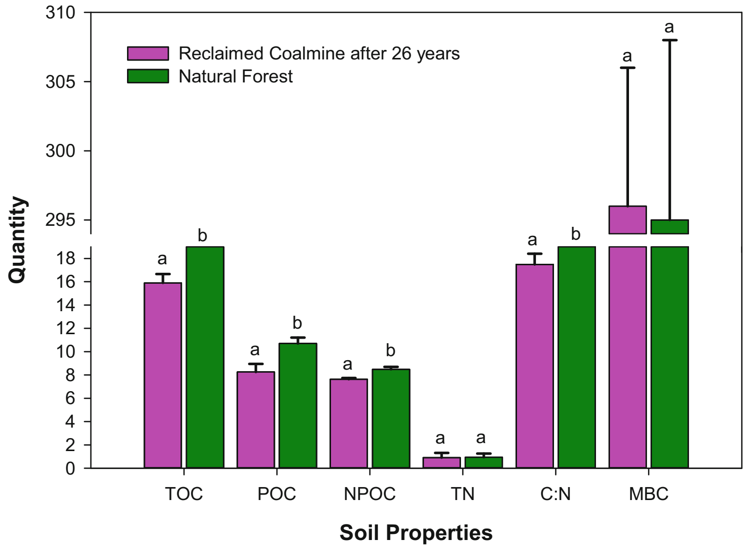

Fig. 10.3 Soil organic carbon pools (total organic carbon, TOC; particulate organic carbon, POC; non-particulate organic carbon, NPOC), total nitrogen (TN), carbon/nitrogen ratio (C/N), and microbial biomass carbon (MBC) of the coal mine sites after 26 years of reclamation and reference forest site. Mean ± standard deviation (SD) ($n = 6$). Letters indicate significant differences for each parameter separately using Duncan multiple range tests (DMRTs) at significant $p < 0.05$ level (ANOVA analysis, $n = 6$). Adapted from Kumar et al. (2018)

suitable environment for fixation of nitrogen (Singh and Chaturvedi 2018). Another chemical effect of organic matter is the remarkable increment of cation exchange capacity (CEC) by the formation of clay-humus complex, which is particularly significant where CEC of a clay mineral is considerably low (Singh and Chaturvedi 2018). Raising CEC improves the retention of nutrients both in naturally recycled vegetation as well as those supplemented with fertilizer (Mukhopadhyay et al. 2016a; Chaturvedi and Singh 2017).

10.4 Controlling Soil Erosion

Vegetation plays a significant role in controlling erosion on gullied areas, land near construction sites, road embankments, landslides, sandstone mines, coal mine spoils, and pipeline corridors (Morgan 2005). The major erosion-prone areas on the coal mine spoil are the overburden banks where erosion occurs very rapidly, and because the habitat is infertile and toxic, the growth of vegetation is very slow (Morgan 2005). Chaturvedi and Singh (2017) emphasized that the only effective method for controlling erosion and the logical path of bringing coal mine spoils back into usefulness is to plant trees and revegetate them. The most important purpose of controlling soil erosion on the infertile and degraded coal mine spoil is to create a stable habitat for the establishment and growth of vegetation. An important objective of the revegetation of coal mine spoils is controlling erosion by increasing plant cover and growth of a self-sustaining plant community through the process of recolonization of particularly native plant species (Huang et al. 2016). Also, for improving the quality of soil in coal mine areas, reclamation has been suggested to be an effective mechanism (Tripathi et al. 2016).

When the coal mine spoils are revegetated with tree plantations, the aboveground components, for example, leaves and stems, absorb significant energy of falling raindrops, flooding water, as well as wind storms, so that their direct impact on soil becomes very less, whereas the belowground components, mainly comprising of root systems, provide mechanical strength to the soil (Morgan 2005). Therefore, after revegetation, the soil of coal mine spoil becomes mechanically stronger which helps to minimize runoff and preserve the soil moisture, which ultimately leads to increase in water availability for the growing plants.

Grass species, such as *Pennisetum pedicellatum* and *Cymbopogon citratus*, and legume plants, such as *Stylosanthes humilis*, *S. hamata*, *Sesbania sesban*, and *Crotalaria juncea*, have been reported to be effective in controlling soil erosion in initial stages of the restoration of coal mine spoil (Maiti and Maiti 2015; Chaturvedi and Singh 2017).

10.5 Improvement of Soil Fertility

The coal mine spoil without plant cover is exposed to harmful effects of torrential rains causing high level of soil erosion; therefore, trees and litter layer are necessary to prevent the soil surface from direct impact of raindrops (Morgan 2005). The biomass of trees after decomposition yield organic matter resulting in improvement of the structure, fertility, as well as other hydro-physical properties of soil (Mukhopadhyay et al. 2016a; Chaturvedi and Singh 2017). Moreover, trees support the growth of other herbs and shrubs which further increase the supply of organic materials to the mine spoil soil through the decomposition of litter, and therefore increase the rate of returning of natural fertility to the degraded fallow land.

Dutta and Agarwal (2002) reported that litterfall from tree plantations act as an important regulating component for the enrichment of microbial biomass on coal mine spoil. The belowground root biomass and aboveground biomass of plants have been observed to be the major source of soil organic matter, and this organic matter is highly associated with microbial biomass in soil (Singh et al. 2006; Chaturvedi and Singh 2017; Singh and Chaturvedi 2018). Kimaro et al. (2007) investigated nutrient use efficiency as well as biomass production of the planted tree species, where after 5 years of rotation, they found that the top soils under *Gliricidia sepium* (Jaqua), *Acacia polycantha*, and *Acacia mangium* were highly enriched with soil organic carbon as well as exchangeable cation. Moreover, the fertility of soil under plantations in their study was very similar to those in the adjoining natural forests.

Tree plantations have been considered to enhance the structural, chemical, and biological properties of soils in various ways. The improvement in soil structure includes stabilization and better aggregation of soil particles, reduction in bulk density, increased water holding capacity, and improvement in infiltration (Mukhopadhyay et al. 2016a). These processes are closely associated with increasing levels of organic matter, enhancement in underground root biomass, and increment in macrofaunal activities (Tripathi et al. 2016). However, these are evenly affected by texture and clay content in soil. Moreover, organic resins as well as fungal and bacterial communities contribute to aggregation of soil particles, leading to structural stability as well as better distribution of pore size, which further provides better water holding capacity, suitable permeability, and aeration, together with good rooting depth, as well as protection from surface erosion (Singh and Chaturvedi 2018). Tree plantations have been reported to accelerate activity of various soil organisms, for example, fungi, earthworms, arthropods, and termites, by providing a cool and moist microclimate under the canopy. Besides, the rhizosphere provides substrate to soil microbial communities that may contribute to their nutrient needs as well as support the production of various growth-promoting substances and other useful biochemicals (Singh and Chaturvedi 2018). Tree plantations increase the nutrient status of coal mine spoil by stabilizing the nutrient cycle by capturing nutrients, which otherwise are leached into deep soil layers (Singh et al. 2002). Due to tree plantations, the cation exchange capacity (CEC) of soil improves, leading to enhancement in nutrient retention and the efficiency of nutrient utilization (Singh et al. 2006; Chaturvedi and Singh 2017). Tree plantations are also known to reduce metal toxicity and elevate pH in soil through enhanced cycling of bases, and by producing various metabolic substances which buffer soil against rapid shift in acidity, alkalinity, and salinity (Sheoran et al. 2010).

Chaturvedi and Singh (2017) reviewed the change in soil properties after tree plantations on the coal mine spoils (Table 10.2). According to their report, soil under 5-year-old plantation accounted 98% higher organic carbon and 67% higher total nitrogen compared to that under 3-year-old plantation. The reported variation of soil C/N ratio (from 8 to 10) could be due to the effect of plantations. However, as observed for soil organic carbon and total nitrogen, the difference was not significant with the age of plantation in mineral N or PO_4-P. Singh and Singh (1999) found that significant amounts of carbon, nitrogen, and phosphorus were immobilized in the biomass of microbial communities and the amount of nutrient immobilization increased with age, which is very similar to the increasing trend of soil organic carbon and total nitrogen (Table 10.2). Singh and Singh (1999) further reported that the associations between microbial carbon and total soil organic carbon, and between microbial nitrogen and total soil nitrogen are significantly positive. As shown in Table 10.2, while the microbial carbon in 5-year-old plantation was 152% greater, microbial nitrogen and phosphorus were observed only 96 and 78% greater compared to the 3-year-old plantation. It is evident that with increase in the age of plantation, proportions of organic carbon, total nitrogen, and total soil phosphorus became greater, leading to immobilization of nutrients in the biomass of soil microbial communities, which highlights the process of redevelopment of the degraded soil.

Table 10.2 Nutrient contents and soil microbial biomass in plantations at different ages in coal mine spoil

Parameters	Plantation age		
	3 years	4 years	5 years
Total organic carbon (C) (%)	0.34[a]	0.50[b]	0.67[c]
Total nitrogen (N) (%)	0.04[a]	0.05[b]	0.07[c]
Total phosphorus (P) (%)	0.01[a]	0.01[a]	0.01[a]
C/N	8.48[a]	9.22[a, b]	10.05[b]
NH_4-N (μg g^{-1})	3.2[a]	3.4[a]	3.7[a]
NO_3-N (μg g^{-1})	0.9[a]	1.1[a]	1.2[a]
Mineral N (μg g^{-1})	4.1[a]	4.5[a]	4.9[a]
PO_4-P (μg g^{-1})	8.0[a]	8.0[a]	8.8[a]
Microbial biomass C (%)	3.77[a]	4.38[a, b]	4.74[b]
Microbial biomass N (%)	4.82[a]	5.38[a]	5.61[a]
Microbial biomass P (%)	7.46[a]	9.45[a, b]	12.13[b]

Adapted from Chaturvedi and Singh (2017)
[a,b,c]Values in a row superscripted with different letters are significantly different from each other at $P < 0.05$

For the long-term restoration of coal mine spoil, it is necessary to establish the stable nutrient cycles supported by the growth of plants and the processes involving microorganisms (Sheoran et al. 2010; de Quadros et al. 2016). Litterfall and the process of decomposition are considered as the starting point for the development of organic carbon and nutrient contents in soil; therefore, the upper soil surface of the coal mine can be treated as a proxy to indicate the status and progress of restoration (Akala and Lal 2000). Ahirwal and Maiti (2018) have clearly described the process of nutrient accumulation in the revegetating coal mine spoil, which is an important mechanism of ecosystem development. Their study suggested that soil is the basic factor of vegetation restoration in coal mine spoils and the condition of soil indicates the direction of vegetation development after reclamation. Therefore, proper understanding of soil dynamics during the process of reclamation and recovery is very significant for planning the future ecological restoration of coal mine spoil. A number of other studies have also highlighted the significance of nutrient dynamics in the revegetation of coal mine soil and its importance in global climate change (e.g., Shrestha and Lal 2011; Mukhopadhyay and Maiti 2014; Mukhopadhyay et al. 2016b; Tripathi et al. 2016).

Vegetation plays a major role in accumulation of organic matter as well as plant nutrients in soil. Similarly, the tree species growing on the reclaimed site have been observed to significantly influence the soil nutrients in the rhizosphere (Table 10.3). Moreover, the microorganisms growing in soil significantly contribute to the reestablishment and functioning of biogeochemical processes and help in the redevelopment and maintenance of the soil fertility. The study by Mukhopadhyay et al. (2016b) indicated that an integrated carbon accumulation index constructed on the basis of the rhizosphere effect of total carbon, labile carbon, and microbial biomass carbon and rhizosphere nitrogen could substantially predict carbon sequestration in

Table 10.3 Tree biomass carbon stock and soil carbon, nitrogen, and phosphorus in the rhizosphere of different tree species growing in the reclaimed coal mine overburden dumps of Chandan opencast project, Jharia Coalfields, Dhanbad, Jharkhand, India (mean ± standard deviation, different letters in the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range test)

Plant species	Total carbon density $tree^{-1}$ (kg)	Total carbon (%)	Microbial biomass carbon ($mg\ kg^{-1}$)	Available nitrogen ($mg\ kg^{-1}$)	Available phosphorus ($mg\ kg^{-1}$)
Acacia auriculiformis	$39.6^{a} \pm 11.5$	$2.27^{c} \pm 0.53$	$162^{c} \pm 38.1$	$89.4^{b} \pm 13.2$	$5.41^{d} \pm 0.65$
Albizia lebbeck	$20.7^{c} \pm 3.89$	$2.47^{b,c} \pm 0.62$	$176^{c} \pm 16.9$	$89.5^{b} \pm 11.7$	$5.63^{d} \pm 0.36$
Cassia siamea	$34.8^{a,b} \pm 9.61$	$4.38^{a} \pm 0.55$	$280^{a} \pm 56.4$	$105^{d} \pm 17.8$	$6.33^{c} \pm 0.23$
Delonix regia	$36.3^{a,b} \pm 11.3$	$3.04^{b} \pm 0.32$	$220^{b} \pm 54.8$	$90.2^{b} \pm 14.4$	$9.43^{a} \pm 0.47$
Dalbergia sissoo	$43.7^{a} \pm 16.1$	$3.99^{a} \pm 0.54$	$228^{b} \pm 28.3$	$84.3^{b} \pm 13.3$	$8.49^{b} \pm 0.37$
Non-rhizosphere mine soil		$4.08^{a} \pm 0.82$	$127^{d} \pm 24.1$	$36.8^{c} \pm 3.08$	$3.40^{e} \pm 0.16$

Adapted from Mukhopadhyay et al. (2016b) reclaimed mine spoils. In several studies, the importance of microorganisms involved in soil formation and plant regeneration through their activities such as decomposition and nutrient cycling, N_2 fixing, and mycorrhizal symbiosis have been broadly recognized. According to Jenkinson and Ladd (1981), the soil microbial biomass (i.e., living part of the organic matter in soil) is an important agent for the conversion of added and native organic matter and serves as an active reservoir for nitrogen, phosphorus, and sulfur in soil. Generally, plants act as an important source of carbon for the development of microbial community, and in return, microbial population provides nutrients for the growth of plants through mineralization (Singh and Chaturvedi 2018). Recognition of the role of soil microorganisms in ecosystem functioning by acting as a source of plant nutrition has now attracted considerable interest toward the measurement of nutrients held in the microbial biomass (Singh and Chaturvedi 2018).

10.6 Carbon Sequestration

Various studies have reported the high potential of restored coal mine sites for atmospheric carbon sequestration; however, the capacity to accumulate carbon may differ according to climatic conditions and plant species used for the restoration of coal mine (Lal 2005; Akala and Lal 2000; Pietrzykowski and Daniels 2014). Table 10.4 summarizes carbon stocks and rate of carbon sequestration in the revegetated mine land or reclaimed forest lands for the studies carried out in different countries. The soil organic carbon sequestration rate has been reported to range from 0.1 to 1.2 Mg C ha^{-1} $year^{-1}$ for the reclaimed forest in Czech Republic (Frouz et al. 2009) and from 0.7 to 5.2 Mg C ha^{-1} $year^{-1}$ for the reclaimed forest in Poland (Pietrzykowski and Daniels 2014). The growth of vegetation cover and modification of soil properties on revegetated sites can lead to a higher carbon sequestration with increment in the age of revegetation (Amichev et al. 2008). According to Kutsch et al. (2009), the respiration by plant roots and microbial communities in soil also results in emission of carbon into the atmosphere.

In a recent study, Ahirwal et al. (2017) have analyzed the effect of revegetation on soil characteristics, in the form of gradual accumulation of soil carbon and nitrogen stock, and variations in ecosystem carbon pool, and soil CO_2 flux at the open strip coal mining project situated in Burmu block of Ranchi District, Central Coalfields Limited (CCL), Jharkhand. According to their results, the nutrient content of the revegetated coal mine soil elevated with the age of revegetation: after 7–11 years of revegetation, soil carbon and nitrogen stocks elevated two times and the carbon sequestration rate registered 1.71 Mg C ha^{-1} $yr.^{-1}$, while the total ecosystem carbon pool increased at the rate of 3.72 Mg C ha^{-1} $yr.^{-1}$. When the revegetated coal mine was resampled after 11 years, the soil CO_2 flux (2.36 ± 0.95 μmol m^{-2} s^{-1}), registered the value four times higher compared to that of the soil of adjoining natural forest. These studies suggest that after plantation, the coal mine soil could act both as a carbon sink and as a source of CO_2 in the terrestrial landscape.

Table 10.4 Comparative analysis of soil carbon stock and rate of carbon sequestration in afforested/reclaimed coal mine areas in different countries

Land use (study area)	Age of reclamation (years)	Soil depth (cm)	SOC stock (Mg C ha^{-1})	SOC sequestration rate (Mg C ha^{-1} $year^{-1}$)	References
Reclaimed forest (Ohio, USA)	25	0–15	37.10	0.2–2.6	Akala and Lal (2000)
Reclaimed forest (Ohio, USA)	20	0–15	14–48.6	1.64	Akala and Lal (2001)
Reclaimed forest (Ohio, USA)	25	0–50	79.9	2.40	Ussiri et al. (2006)
Reclaimed forest (Singrauli, India)	05	0–20	3.8–11.1	0.1–3.2	Singh et al. (2006)
Reclaimed forest (Czech Republic)	22–32	0.10	4.5–38.0	0.1–1.2	Frouz et al. (2009)
Reclaimed forest (Poland)	24	0–110	16.8–65.0	0.7–5.2	Pietrzykowski and Daniels (2014)
Revegetated mine land (Singrauli, India)	19	0–30	22.9	1.3	Tripathi et al. (2014)
Reclaimed forest (Jharkhand, India)	7–11	0–30	11.4–24.4	1.2–2.2	Ahirwal et al. (2017)

Source: Ahirwal et al. (2017)

10.7 Conclusion

This communication describes the role of tree plantations in recovery of the degraded coal mine spoil which has toxic and unfavorable environment for the growth of vegetation. This review explains the harmful effects of coal mining which results in the degradation of soil by destructing its physical, chemical, and biological structure, accelerating soil erosion, enhancing nutrient leaching, making soil compact by overburden dump, reducing soil pH, accumulating heavy metals in soils, depleting soil organic matter, decreasing plant available nutrients, reducing CEC, and decreasing microbial activity. This study suggests that revegetation through tree plantations is one of the efficient methods for restoring the fertility of soil by improving the organic matter content and its various properties, by increasing plant available nutrients and CEC, and incrementing biological activities. From this review, it may be concluded that the revegetation of coal mine spoil through tree plantations can improve fertility of soil and can support the establishment of vegetation; however, the process of restoration of the vegetation, close to the original level, may take longer time, depending on the extent of degradation. Based on literature survey, this study suggests some promising tree species that could be used for revegetating coal mine spoils, viz., *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria*. These tree species are acid-tolerant, suitable for growing in infertile soil, and are able to add substantial quantity of organic matter to the soil.

For achieving long-term sustainability in the mining area, restoration process should be aimed to construct an ecosystem that is abundant with native species (Singh et al. 2004a; Chaturvedi and Singh 2017). In the process of ecological restoration, priority should be given toward the persistence of species through natural establishment and survival, factors influencing functioning of food webs, as well as system-wide nutrient conservation through interactions among the community of animals, plants, and organisms involved in decomposition (Jackson et al. 1995). In the process of mining, the top soil is removed, soil seed bank and root stocks are excavated, and the overall soil profile is disturbed, leading to slowing down of the natural succession process on coal mine spoils. However, it has been reported that the revegetation process may be enhanced by plantations of suitable native species together with addition of herbaceous species via ground seeding (Singh et al. 1996).

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Carbon Sequestration Potential of Agroforestry Systems for Rehabilitating Degraded Lands of India

11

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Abstract

Degradation of land is a very vital question to be addressed in present times and needs immediate attention for restoration. There are various kinds of land degradation processes in India such as water and wind erosion, waterlogging, soil salinity and alkalinity, soil acidification, loss of soil organic matter, and other complex processes. The increasing level of CO_2 in the atmosphere along with other greenhouse gases is a big concern for human society. Agroforestry as such is a very cost-effective and viable option not only for sustaining productivity but also for having socioeconomic and environmental benefits. Agroforestry has the long-term potential to combat climate change, maintain soil health, improve biodiversity, and protect natural resources. Sequestering C through agroforestry is now considered as an alternative economic opportunity for the mitigation of global climate change and carbon trading in addition to providing multiple associated benefits. The present review discusses role of agroforestry systems for degraded land management with main focus on carbon sequestration. The study undertaken under NICRA (National Innovations in Climate Resilient Agriculture) Project at ICAR-Central Agroforestry Research Institute, Jhansi, for 17 states of India, revealed that total carbon stock under baseline in different states of the country varied from 14.5 to 33.48 Mg C ha^{-1}. Carbon sequestration potential in agroforestry systems existing on farmers' field varied from 0.11 to 0.82 Mg C ha^{-1} per year. The inference was drawn that these systems especially in degraded landscapes have tremendous scope of locking carbon and mitigating climate change; however, the magnitude of carbon sequestration would vary depending on the climatic and geographical conditions of the area.

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Keywords

Agroforestry systems · Carbon sequestration · Mitigation of climate change · Degraded landscapes

11.1 Introduction

Land degradation is the reduction in the capacity of the land to provide ecosystem goods and services and assure its functions over a period of time for the beneficiaries of these (FAO 2015). In India, 29.3% of the geographical area has undergone land degradation, with maximum contribution from water erosion, acidification, wind erosion, desertification, salinization, and mining (ISRO 2018). It is estimated that nearly 79% of the wastelands occur in the states of Andhra Pradesh, Telangana, Uttar Pradesh, Uttarakhand, Gujarat, Karnataka, Madhya Pradesh, Chhattisgarh, Maharashtra, Orissa, Rajasthan, Tamil Nadu, Bihar, and Jharkhand (NBSS & LUP 2005; Bhattacharyya et al. 2015).The degradation is largely caused due to both natural and anthropogenic activities making the land to become unproductive, but by proper rehabilitation measures, they can be brought under cultivation successfully. Land degradation fundamentally affects crop productivity, biological diversity, hydrological cycles, nutrient transformation, ground water quality, and overall socioeconomics of the region concerned. The proper management of natural resources through planting trees helps in maintaining environmental balance of agro-ecosystems (Bremer and Farley 2010).

There is increasing research interest in the carbon sequestration potential, processes, and mechanisms in agroforestry systems (Nair et al. 2009a, b; Zomer et al. 2016). The C sequestration potential of AF has been estimated in a number of studies, but the estimates at the global scale vary widely (Kim et al. 2016; Cardinael et al. 2018). The estimates of C accumulation in different AF systems ranged from 0.29 to 15.2 Mg C ha^{-1} $yr.^{-1}$in aboveground plant components and from 30 to 300 Mg C ha^{-1} $yr.^{-1}$ for soils up to 1 m depth (Nair et al. 2009b). Agroforestry systems provide options to mitigate climate change with the possibility of increasing in crop yields and providing other positive environmental outcomes such as climate change adaptation (Coulibaly et al. 2017; Waldron et al. 2017).

In India, carbon sequestration potential of AF systems is estimated as 0.25–76.55 Mg C ha^{-1} yr^{-1} for tree and 3.98 Mg C ha^{-1} yr^{-1} for soil organic carbon (Dhyani et al. 2016). However, this potential varies with region, types of species, age of agroforestry system, environmental condition, and previous land history (Kaul et al. 2010). Livelihood of most of the farmers of arid and semiarid region of India mainly depends on rainfed agriculture and animal husbandry. The Himalayan region and downstream areas are very vulnerable to climate change. Long-term trends in the maximum, minimum, and mean temperatures over the northwestern Himalayas during the twentieth century have suggested a significant rise in air temperature, decrease in precipitation, and reduction in snowfall with winter warming occurring at a faster rate (Bhutiyani et al. 2007; Dimri and Kumar

2008). In the context of climate change, the Himalayan region could suffer wide-ranging environmental and socioeconomic impacts that could seriously affect and alter the distribution, type, and quality of natural resources of the region (Beniston 2003). The United Nations Framework Convention on Climate Change defines carbon sequestration as the process of removing carbon from the atmosphere and depositing it in plants, soils, geologic formations, and the ocean for a long term. Projections of the World Agroforestry Center have indicated that the carbon market may exceed US$1 trillion by 2025, and significant funds could potentially be generated through agroforestry.

According to the latest IPCC report (2014), changes in climate are unequivocal and anthropogenic greenhouse gases (GHG) are the major drivers of this change. As to tackle vagaries of climate change, various policies are put in force throughout the world, even though average annual GHG emissions grew by 1.0 gigatonne carbon dioxide equivalent (Gt CO_2 e) which is 2.2% per year from 2000 to 2010 as compared to 0.4 GtCO_2 e (1.3%) per year from 1970 to 2000. Total anthropogenic GHG emissions were highest in human history from 2000 to 2010 and reached 49 ($\pm$4.5) Gt CO_2 eq yr^{-1} in 2010 (IPCC Working Group III AR5 2014). Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reduction over the next few decades can reduce climate risks in the twenty-first century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term, and contribute to climate-resilient pathways for sustainable development. Ecosystem-based options like ecological restoration, soil conservation, afforestation, reforestation, agroforestry, mangrove conservation and replanting, green infrastructure (e.g., shade trees, green roofs), controlling overfishing, fishery co-management, assisted species migration and dispersal, ecological corridors, seed banks, gene banks and other ex situ conservation, and community-based natural resource management are the future strategies to mitigate climate change in a sustainable manner. Substantial research on climate change, its impact on agriculture, ways, and means for stabilizing the atmospheric CO_2 concentration and reducing the CO_2 emissions or increasing the carbon sink has been carried out. Currently researchers and planners are attempting to increase the carbon storage capacity of terrestrial vegetation through land use practice such as afforestation, reforestation, and agroforestry.

Today, agroforestry system (AFS) has become an established approach to integrated land management, not only for renewable resource production but also for climate change mitigation and land reclamation. The carbon storage capacity of agroforestry varies across the species and geography. Improved carbon storage of the agroforestry system can also be explained because of enhanced biomass production that is partly returned to the soil through litter both aboveground and belowground parts of the plants (Newaj et al. 2017). Further, the amount of carbon in any agroforestry system depends upon the structure and function of different components within the system. In this context, there is lot of scope for carbon sequestration through agroforestry systems for rehabilitating degraded lands. The present review aims to discuss agroforestry system for rehabilitation of degraded lands with a main focus on carbon sequestration.

11.2 Extent of Land Degradation in India

According to the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP 2005), 146.8 million-hectare land is degraded in India due to various processes of degradation such as water and wind erosion, waterlogging, soil salinity and alkalinity, soil acidification, and other complex processes. The report-cum-atlas showed that during 2011–2013, 29.3% of the country was undergoing land degradation (ISRO 2018). In India, it is estimated that nearly 79% of the wastelands are in the states of Andhra Pradesh, Telangana, Uttar Pradesh, Uttarakhand, Gujarat, Karnataka, Madhya Pradesh, Chhattisgarh, Maharashtra, Orissa, Rajasthan, Tamil Nadu, Bihar, and Jharkhand (Table 11.1; NBSS & LUP 2005; Bhattacharyya et al. 2015). The top process leading to degradation/desertification in the country was stated to be water erosion (10.98% in 2011–2013) followed by vegetation degradation (8.91%) and wind erosion (5.55%). Overall, the areas affected by vegetation and water erosion increased by 1.02 Mha and 0.49 Mha, respectively, in 2011–2013. In terms of India's total geographical area, the states of Rajasthan, Gujarat, Maharashtra, Jammu and Kashmir, and Karnataka have the highest area of lands undergoing degradation/desertification, amounting to 18.4% (out of India's total 29.3% degraded land), while all the other states each had less than 2% of degraded lands. Water erosion is the most serious degradation problem in India, resulting in loss of topsoil and terrain deformation.

Based on soil loss data, the average soil erosion rate is 16.4 Mg ha^{-1} $year^{-1}$, resulting in an annual total soil loss of 5.3 billion tons throughout the country (Dhruvanarayan and Babu 1983). Apart from faulty agricultural activities that led to soil degradation, other human-induced land degradation activities include land clearing and shifting cultivation, deforestation, overgrazing, surface mining, and industrial development (Bhattacharyya et al. 2015). Due to overgrazing and deforestation, more than 20% area has turned into wastelands in eight Indian states. High livestock density in arid regions causes overgrazing, resulting in decreased infiltration and accelerated runoff and soil erosion. Due to overgrazing, soil loss is 5–41 times greater than normal at the mesoscale and 3–18 times greater at the macro scale (Sharma 1997). Overburden removal from mine area results in significant loss of vegetation and rich topsoil; and mineral production generates enormous quantities of waste/overburden, and a huge land area is degraded due to this process (Sahu and Dash 2011).

Bhattacharyya et al. (2015) have indicated that agricultural activities and practices can cause land degradation because of cultivation in fragile deserts and marginal sloping lands, land clearing through clear felling and deforestation, depletion of soil nutrients through poor farming practices, overgrazing, excessive irrigation, over drafting, urban sprawl and commercial development, and industrial waste disposal to arable lands. ISRO's Space Applications Centre in Ahmedabad released the results of a project in 2018 in the form of an Atlas, mapping the extent of land degradation and desertification across the country, including the processes involved the severity, and the changes in degradation.

Table 11.1 The extent of various kinds of land degradation in major states of India (Mha)

State	Water erosion	Wind erosion	Waterlogging	Salinity/ alkalinity	Soil acidity+complex problem	Total degraded area (Mha)	% of degraded area to TGA
Andhra Pradesh + Telangana	11.5	0	1.9	0.5	0.9 + 0.2	15.0	54.5
Karnataka	5.8	0	0.9	0.1	0.1 + 0.7	7.6	39.8
Jammu and Kashmir	5.5	0.1	0.2	0	0	7.0	31.6
Uttar Pradesh + Uttarakhand	11.4	0.2	2.4	1.4	0	15.3	52.0
Bihar + Jharkhand	3.0	0	2.0	0.2	1.0 + 0	6.3	36.1
Gujarat	5.2	0.4	0.5	0.3	1.7	8.1	41.5
Rajasthan	3.2	6.7	0	1.4	0+ 1.7	11.4	33.2
Madhya Pradesh + Chhattisgarh	17.9	0	0.4	0	7 + 1.1	26.2	59.1
Maharashtra	11.2	0	0	1.1	0.6 + 0.3	13.1	42.4
Orissa	5.0	0	0.7	0	0.3 + 0.1	6.1	39.3

Data source: NBSS and LUP (2005) on 1:250,000 scale. TGA is total ground area

The degradation is largely caused due to both natural and anthropogenic activities causing the lands to become unproductive, but by proper rehabilitation measures, they can be brought under cultivation. Land degradation per se is fundamentally affects crop productivity, biological diversity, hydrological cycles, nutrient availability, ground water quality, and overall socioeconomics of the region concerned. The Bonn Challenge is a global effort to bring 150 million hectares of deforested and degraded land into restoration by 2020 and 350 million hectares by 2030. The government of India made a Bonn Challenge pledge to bring under restoration 13 million hectares of degraded land by 2020 and an additional eight million hectares by 2030. These lands have tremendous scope of carbon sequester if brought under agroforestry systems. Some of these efforts have been explained in this chapter.

11.3 Agroforestry Systems for Rehabilitation of Degraded Lands

There are several methods to rehabilitate a degraded land based on the severity of the damage caused and the resources we have for proper rehabilitation. The IUCN guidelines for the restoration of degraded ecosystems define restoration as process bringing a degraded ecosystem or landscape back to same prescribed, productive condition in short process of revitalization (Lamb 1988). Vegetation helps in amelioration of microclimatic conditions and marking catalytic effect on succession on severely degraded sites (Parrotta 1992). Agroforestry assumes significance in the production of both local commodities such as fuelwood, timber, fruit, and fodder and the globally traded ones such as coconut, coffee, tea, cocoa, and rubber (FAO 2013). Combining trees and crops in spatial or temporal arrangements has been shown to improve food and nutritional security and mitigate environmental degradation, offering a sustainable alternative to monoculture production (Nair 2007). We have gone long way to evaluate and identify suitable plant species for site-specific situations in the world and developed required agroforestry technologies for various problematic areas to sustain livelihood security and render environmental services but require strategies and policies for getting these results implemented (Dagar et al. 2014). Some agroforestry systems suitable for rehabilitating degraded lands by soil erosion, salinization, waterlogging, mining, and loss of soil fertility in India are briefly discussed in the following sections:

11.3.1 Agroforestry Systems for Salt-Affected Soils

Studies conducted in India reveal that the best model for the bio-saline agroforestry plantation is the use of relatively high-value tree species (*Populus deltoides*, *Prosopis juliflora*, *Eucalyptus tereticornis*, and *Acacia nilotica*) (Table 11.2) in combination with grasses such as *Leptochloa fusca* during the initial few years and arable crops such as rice and wheat in the subsequent years (Singh et al.

Table 11.2 Suitable tree species for degraded lands in India

Degraded lands	Suitable tree species
Saline soils	*Casuarina glauca*, *Casuarina equisetifolia*, *Prosopis juliflora*, *Salvadora persica*, *Salvadora oleiodes*, *Tamarix articulata. Tamarix troupii*, *Parkinsonia aculeata*
Alkali soils	*Prosopis juliflora*, *P. cineraria*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata*, *Pongamia pinnata*, *Butea monosperma*, *Feronia limonia*, *Eucalyptus tereticornis*, *Moringa oleifera*, *Mangifera indica*, *Pyrus communis*
Acid soils	*Acacia mangium*, *Acacia auriculiformis*, *Cassia siamea*, *Calliandra calothyrsus*, *Pinus roxburghii*, *P. wallichiana*, *Celtis australis*, *Acacia mearnsii*, *A. decurrens*, *A. dealbata*, *A. pycnantha*, *Manilkara hexandra*, *Phoenix* spp., *Pterocarpus marsupium*, *Shorea robusta*, *Hardwickia binata*, *Terminalia* spp., *Tectona grandis*, *Gmelina arborea*, *Xylia xylocarpa*, *Bamboo* spp., *Alnus* spp. among agri-horti system—mango, peach, orange, grapes, banana, kiwi fruit, pineapple, guava. etc.
Ravine land	Euca*lyptus* species, *Dendrocalamus strictus*, *Morus alba*, *Broussonetia papyrifera*, *Dendrocalamus strictus*, *Gmelina arborea*, *Dalbergia sissoo*, *Tectona grandis*, *Azadirachta indica*, *Leucaena leucocephala*, and *Prosopis juliflora*
Mine spoils	*Acacia auriculiformis*, *A. nilotica*, *Dalbergia sissoo*, *E. camaldulensis*, *Agave americana*, *Bauhinia retusa*, *Buddleja asiatica*, *Grevillea pteridifolia*, *Salix tetrasperma*, *Pinus* spp., *Grewia tenax*, *P. juliflora*, *Albizia lebbeck*, bamboos, and grasses such as *Arundo donax*, *Saccharum spontaneum*, *Cenchrus setigerus*, *Cymbopogon* spp., *Cynodon dactylon*, *Dichanthium annulatum*, etc.
Waterlogged soils	Species of *Casuarina*, *Pongamia*, *Eucalyptus*, *Acacia*, *Terminalia*, *Syzygium*, *Dalbergia*
Sand dunes stabilization	*Prosopis cineraria*, *Acacia cupressiformis*, *Pongamia pinnata*, *Acacia tortilis*, *Acacia nilotica*, *Prosopis juliflora*, *Azadirachta indica*, *Tecomella undulata*, *Azadirachta indica*, *Melia azedarach*, *Albizia lebbeck*, *and Ailanthus excelsa*
Coastal soils	*Avicennia officinalis*, *Ailanthus malabarica*, *Excoecaria agallocha*, *Bruguiera cylindrica*, *B. parviflora*, *B. gymnorrhiza*, *B. sexangula*; species of *Rhizophora*, *Ceriops*, *Sonneratia*, *Xylocarpus*; *Salicornia bigelovii*, *Salvadora persica*, *S. oleoides*, *Terminalia catappa* species of *Pandanus*, *Borassus flabellifer*, *Anacardium occidentale*, etc.

Source: Adapted from Dagar (2014), Uthappa et al. (2015)

1997). There are evidences that in moderately alkaline soils, where tree-based systems were adopted, the microbial biomass C and N were found to be more than mono-cropping (Kaur et al. 2000). Studies conducted in the Bichhian Reserve Forest of Saraswati Range in Kurukshetra District, Haryana, *Leptochloa fusca*-*Prosopis juliflora*-based silvopastoral system found to be most suitable combination for highly sodic soils in terms of productivity and soil amelioration (Singh and Dagar 2005). 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). Dagar et al. (2001b), Khan (2003), Singh et al. (2008), 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. Tomar et al. (1998) in long-term studies found that *Acacia tortilis*, *A. farnesiana*, *Casuarina glauca*, *Eucalyptus camaldulensis*, *Salvadora oleoides*, *Parkinsonia aculeata*, and *Tamarix* spp. are the ideal trees for waterlogged saline soils.

11.3.2 Bio-drainage for Waterlogged Soils

In India, the total degraded land due to water-logging has been estimated to be 6.41 M ha out of which 1.66 M ha is due to surface ponding and 4.75 M ha is under sub-surface water-logging (Maji et al. 2010). The development of waterlogged soils mainly arises due to unprecedented use of irrigation water without proper drainage mainly in the canal areas of western India. This problem further aggravates the problem of salinization. It is very cost-effective to ameliorate the waterlogged soils with sub-surface drainage system, which is not always viable. But, however, we have the tool of bio-drainage plants or trees, which have the potential to take up excess water in their system through their deep-rooted systems. It was found through scientific evidences that the species such as *Eucalyptus*, *Casuarina* spp., *Populus deltoides*, *Acacia nilotica*, *Prosopis spp.*, *Pongamia pinnata*, etc. reduce the seepage loss and thus, ameliorate waterlogged soils in several places of Indo-Gangetic Plains and coastal Orissa areas (Dagar 2014). Heuperman et al. (2002) concluded that the plantations act like groundwater pumps, pumping water at the rate of 34,460 $m^3 yr^{-1}$ or 3.93 $m^3\ hr^{-1}\ ha^{-1}$ of plantation and the water used by plantations in the IGNP command was 3446 mm yr^{-1}, which was about 1.4 Class A pan. For more details see Dagar and Minhas (2016). 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 physico-chemical properties of soil also improved to greater extent, more so in block plantations.

11.3.3 Ameliorating Acid Soils

There are about 90 million hectares of acid soils spread across several states concentrating in southern peninsular region, northeastern region, Himachal Pradesh, Jammu and Kashmir, and Uttarakhand. Out of these, 31-million-hectare area shows severe soil acidity problems ($pH < 5.5$) and 51 million hectares has pH between 5.6 and 6.5 (Sharma and Sarkar 2005a, b; NAAS 2010). Severely acidic soils like acid sulfate soils (pH 4.5 or less) are found in coastal areas such as Kuttanad area of Kerala, Goa, Maharashtra, and Andaman and Nicobar Islands (Ganeshamurthy et al. 2000). Amelioration of acid soil with lime is the most favored practice, as lime raises the soil pH and thus makes all other essential nutrients available to plant roots and reduces toxicity of Fe and Al (Sharma and Sarkar 2005a, b; Fageria and Baligar 2008; Bhat et al. 2007). Acid soils developed in coastal areas or peninsular India are mostly due to more rainfall than evaporation and continuous ponding. The soils are having very low pH and red to yellow in color due to excess of Al and Fe. The presence of excess Al may be catered by judicious use of compost and other materials along with lime, thus increasing the pH, and on the other the presence of toxic levels of Fe may be reduced by having good draining so that the Fe will be in ferric form and will be less harmful. The acid-tolerant tree and fruit crops may be advocated for the region. Besides mangroves, tree species such as *Thespesia populnea*, *Terminalia catappa*, *Borassus* palm, Coconut (*Cocos nucifera*), areca nut (*Areca catechu*), *Acacia auriculiformis*, *Pandanus* spp., *Casuarin*a spp., cashew (*Anacardium occidentale*), and oil-yielding *Salicornia* are ideal species for these areas (Dagar et al. 2014).

11.3.4 Agroforestry for Ravine Lands

The word "ravines" mainly denotes the last stage of water erosion, where the deep gullies run parallel to each other and meet the river at very short distances. The topography of ravine lands is very typical with mainly due to less vegetation or no vegetation on top portions of ravines, due to severe water erosion. The topsoil erodes down and leaving cracks behind; in due course of time, these cracks deepen and lead to form ravines of varying degrees and sizes. The area of ravines has very meager rainfall and lies mostly in semiarid to sub humid conditions. Verma and Bhushan (1986) proposed gully reclaimability ratings by classifying following six classes:

Class 1: Shallow gullies which require minor leveling work on gently sloping sides on bed for reclamation for agriculture. They have favorable soil texture for most of the crops. The bed may be wide enough to be converted into agricultural fields with minor shaping. Good management practices are required.

Class 2: Gullies which require moderate leveling work for reclamation for agriculture. The gullies are 1.5–3.0 m deep, and sides are more sloping than in Class 1. Maintenance of reclaimed plots requires more care of terrace faces.

Class 3: It has got more limitations than Class 2 of reclaimability class gullies. Soil texture may be lighter or heavier than loam, and the gully may be deeper, presenting more limitation for reclamation and management of reclaimed gully for cropping.

Class 4: It has severe limitations for reclamation for agriculture in the soil texture or gully dimensions. Steeper side slopes and more gully depth constitute a borderline case for reclamation for cropping. Such gullies may be put under agri-horticulture after constructing narrow terraces.

Class 5: This category includes gullies described in Classes 1–4, but they cannot be gainfully reclaimed for agriculture as they are prone to seasonal backflows from a nearby river or have developed waterlogging, salinity problems, etc., due to irrigation of the adjoining table land or any other adverse factors. Under such very adverse conditions, gullies may be put under perennial vegetation like suitable fuel and fodder trees and grasses (silvo-pasture). Grass cutting for stall-feeding may be allowed. Fuel trees may be exploited on rotation basis.

Class 6: Gullies presenting limitations more severe than Class 4 in soil characteristics like texture and gully features like depth and side slopes are included in this category.

Dagar and Tewari (2017) have reported the kind of perennial vegetation suitable for various classes of reclaimability. In the gullies belonging to reclaimability Classes 1, 2, and 3, all local crops such as sorghum (*Sorghum durra*), maize *(Zea mays*), pearl millet (*Pennisetum typhoides*), wheat (*Triticum aestivum*), green gram (*Vigna radiata*), black gram (*V. mungo*), pigeon pea (*Cajanus cajan*), gram (*Cicer arietinum*), mustard (*Brassica juncea*), and tobacco (*Nicotiana tabacum*) can be grown in gully beds and on bench terraces made on gully sides. Class 4 may be put under arable crops along with fruit trees such as lemon (*Citrus limon*), mango (*Mangifera indica*), ber (*Ziziphus mauritiana*), and aonla (*Emblica officinalis*) at required spacing in agriculture crops in gully beds. Classes 5 and 6 may be planted under perennial vegetation like fuel and fodder producing trees and grasses.

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. Grasses such as *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 (Dagar 2018a, b). After protecting from grazing silvopastoral system, involving the abovementioned 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. For more details see publication of Dagar (2018a, b) and recently publication brought out by Dagar and Singh (2018) who have compiled research carried out globally on greening of eroded habitats for livelihood and environmental security.

11.3.5 Mine-spoiled Rehabilitation

According to report of the Union Ministry of Mines (Ministry of Statistics and Program Implementation, Govt. of India), 53 abandoned mines covering an area of about 660 ha were reclaimed/rehabilitated in 2007–2008, and about 1135 mines covering 11200 ha area were still under rehabilitation program. Especially in the mined soils, the quality of soil highly deteriorates, due to excessive use of blasting materials, low moisture, and high temperature and thus leads to exposure of subsurface soils or bed rocks. The magnitude of impact intensifies when mine lease is close to the river and drainage flow is toward the river (Chaterjee 1988; Verma 1988; Dadhwal et al. 1992). Rehabilitating the mine soils is highly challenging on the face of magnitude of damage. Though the choice of species and site preparation before planting, after care, legal provisions, etc are important aspects. Vegetation is the most appropriate and cost-effective long-term remedy to encounter the majority of underlying problems of derelict mined land (Bradshaw 1997).

11.3.6 Agroforestry for Sand Dune Stabilization

The arid region in India comprises about 3,00,000 km^2 covering over six states. Mostly, it falls under western region of India. The region specifically infused the indigenous tree species practiced on farmers' field since long. The region is having 200–400 mm rainfall with erratic pattern mostly during July–September. Farmers mostly grow mixed cropping as an insurance against delayed or monsoon failures and also to provide economic stability. The top feed species of *Prosopis cineraria* (Khejri) and *Ziziphus* spp. are maintained in the agricultural fields to meet the fuel and fodder requirements of the farmers in dry regions of Rajasthan and Haryana. In the Jaisalmer region, people have "khadin" system of indigenous water harvesting methods to grow *rabi* crop during availability of water. Despite the hostile environment, there is large population of livestock, and many a times, due to fodder requirement needs, overgrazing is done, which further leads to degradation and desertification. *Acacia tortilis*—*Albizia lebbeck*—*Cassia siamea*—*Prosopis juliflora* are the species practiced for shelter belt plantation which remains effective for reducing the wind speeds and deflecting the winds.

For sand dune fixation, it is essential to protect the young seedlings from abrasive action of the winds. It can be done by using parallel hedge system in the direction of the wind. Locally available plant species such as *Leptadenia pyrotechnica*, *Ziziphus* *nummularia*, *Calligonum polygonoides*, *Lasiurus sindicus*, *Panicum turgidum*, and *Erianthus limja* are used for this purpose by burying them vertically downward across the wind direction in rows 2–3 m apart particularly at the crest of the dune at 5–10 m toward the base.

After fixation of sand dunes, the plantings should be done either through direct seeding or transplanting the seedlings or cuttings of appropriate agroforestry species. The success of sand dune stabilization mainly depends upon choice of species, planting methods, deep plantation, proper care, causality replacement, etc. Kaul (1985) reported that trees species such as *Prosopis juliflora*, *Calligonum polygonoides*, *Crotalaria burhia*, *Aerva javanica*, *Ziziphus nummularia* (shrub), and *Lasiurus sindicus*, *Panicum turgidum. Panicum antidotale* (grasses) are most suitable plant species for sand dune stabilization in the arid zone of western Rajasthan. The development of a permanent cover of grasses like *Lasiurus sindicus*, *Cenchrus ciliaris*, *Panicum turgidum*, *Cenchrus biflorus*, etc. through their extensive root system helps to binds the sand and protects it from moving away, being a regular source of fodder for the livestock.

11.3.7 Agroforestry for Improving Soil Health

Soil is one of the most precious resources for any type of agroforestry system development. But, nevertheless, it has been irrationally being used, and due to lot of abiotic and human-induced damage, its potential for sustaining the vegetation as well as resilience toward any pervert has been declined. As stated in earlier sections, all the trees contribute toward increasing organic matter into the soil through litter fall and decomposition of fine roots, hence addition of nutrients. There are evidences that leguminous trees in alley cropping systems can contribute as much as 358 kg nitrogen ha^{-1}, 28 kg phosphorus ha^{-1}, 232 kg potassium ha^{-1}, 144 kg calcium ha^{-1}, and 60 kg magnesium ha^{-1} (Palm 1995). The trees like species of *Indigofera*, *Leucaena*, *Sesbania*, and *Cajanus* when grow under alley cropping system can add lot of nitrogen to the soil.

11.4 Carbon Sequestration Potential of Agroforestry Systems

The United Nations Framework Convention on Climate Change (UNFCCC) defines carbon sequestration as the process of removing C from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric CO_2 and its secure storage in long-lived pools (UNFCCC 2007). The carbon cycle in plants is driven by the process of photosynthesis (Fig. 11.1).

Agroforestry systems can be better climate change mitigation option than ocean, and other terrestrial options, because of the secondary environmental benefits such as food security and secured land tenure, increasing farm income, restoring and maintaining aboveground and belowground biodiversity, and maintaining watershed hydrology and soil conservation (Yadava 2010). Singh and Pandey (2011) describe

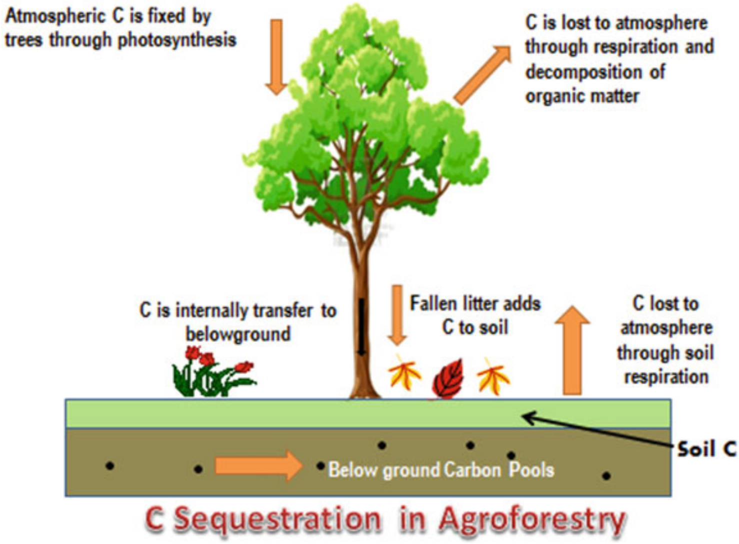

Fig. 11.1 The carbon cycle in plants is driven by the process of photosynthesis (Source: Newaj et al. 2014)

the agroforestry for carbon sequestration attractive because (1) it sequesters carbon in vegetation and in soils depending on the pre-conversion soil C, (2) more intensive use of the land for agricultural production reduces the need for slash-and-burn or shifting cultivation, (3) the wood products produced under agroforestry serve as substitute for similar products unsustainably harvested from the natural forest, (4) to the extent that agroforestry increases the income of farmers, it reduces the incentive for further extraction from the natural forest for income augmentation, and, finally, (5) agroforestry practices may have dual mitigation benefits as fodder species with high nutritive value can help to intensify diets of methane-producing ruminants while they can also sequester carbon. Agroforestry enhance the uptake of CO_2 or reduce its emission and has the potential to remove a significant amount of CO_2 from the atmosphere if the trees are harvested, accompanied by replanting of same and/or other area, and sequestered carbon is locked through non-destructive use of such wood. Many researchers have proved that agroforestry system are promising land use systems to increase aboveground and soil C stock to mitigate greenhouse gas emissions (Sathaye and Ravindranath 1998; Verchot et al. 2006; Yadava 2010; Chavan et al. 2015). The carbon sequestration potential of tropical agroforestry systems is estimated between 12 and 228 Mg ha^{-1} with a mean value of 95 Mg ha^{-1} (Pandey 2007). Therefore, based on global estimates of the area suitable for agroforestry (585–1215 $\times$ 10^6 ha), 1.1–1.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years (Albrecht and Kandji 2003).

Agroforestry has importance as carbon sequestration strategy because of C storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. Agroforestry can also have an indirect benefit on C sequestration when it helps to decrease pressure on natural forests, which are the largest sinks of terrestrial C. Another indirect avenue of C sequestration is through the use of agroforestry technologies for soil conservation, which could enhance C storage in trees and soils. For increasing the C sequestration potential of agroforestry systems, practices such as conservation of biomass and soil carbon in existing sinks, improved lopping and harvesting practices, improved efficiency of wood processing, fire protection and more effective use of burning in both forest and agricultural systems, increased use of biofuels, and increased conversion of wood biomass into durable wood products are advocated to be exploited to their maximum potential. Agroforestry, thus, contributes to the resilience of agriculture by adaptation and mitigation of climate change effects. In India, evidence is now emerging that agroforestry systems are promising land use system to increase and conserve aboveground and soil carbon stocks to mitigate climate change (Dhyani et al. 2009). Average sequestration potential in agroforestry in India has been estimated to be 25 Mg C ha^{-1} over 96 million ha (Sathaye and Ravindranath 1998). In another estimate agroforestry contributes 19.30% of total C stock under different land uses.

The potential of agroforestry systems as carbon sink varies depending upon the species composition, age of trees, geographic location, local climatic factors, and management regimes. In an agri-silvicultural system, *Dalbergia sissoo* at age of 11 years was able to accumulate 48–52 Mg ha^{-1} of biomass (Newaj and Dhyani 2008). Carbon dynamics involving different pruning treatments were studied in an agri-silvicultural system where tree biomass was 23.61–34.49 Mg C ha^{-1} with black gram-mustard. The bamboo and trees have very different sequestration patterns but are likely to have comparable carbon sequestration capacity, as long as the bamboo is managed and the total amount of harvested fiber is turned into durable products. Tropical *Bambusa bambos* produced total aboveground biomass 287 Mg ha^{-1} with a mean annual production of around 47.8 Mg ha^{-1} yr^{-1}, almost twice that of the *Eucalyptus* clones. The total biomass of mature bamboo at 6 years was found to be higher than that of teak (*Tectona grandis*) at 40 years, that is, 149 Mg C ha^{-1} as compared to only 126 Mg C ha^{-1} for teak. Every 5 years bamboo would produce at least 86 Mg ha^{-1} biomass and sequester 43 Mg C ha^{-1}, almost twice as much as a teak plantation under the similar conditions. Thus, to achieve higher level of carbon sequestration, sustainable bamboo management, regular harvesting, and utilization for durable products should be advocated. The literature indicates that agroforestry systems has the potential to sequester large amounts of above and belowground carbon in addition to SOC enhancement, as compared to treeless farming systems (Ajit et al. 2013).

On degraded soils, tree-based systems have tremendous potential of locking carbon in wood biomass. In one study, Singh et al. (1993) observed that a biomass (firewood and small timber) of 26, 21, 19, and 15 Mg ha^{-1} from 6-year-old plantations of *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, and *Eucalyptus tereticornis*, respectively, was obtained from highly alkali soil with pH > 10. Dagar et al. (2001b) harvested 51, 70, and 93 Mg ha^{-1} biomass from 7-year-old *P. juliflora*, *A. nilotica*, and *Tamarix articulata*, respectively, from sodic soil with original pH 10.3, and the increase in organic carbon under respective species was 0.23, 0.26 and 0.10%. *T. articulata* ameliorated the soil by inducing the maximum reduction of exchangeable sodium percentage (ESP) and pH values followed by *P. juliflora* and *A. nilotica*. From a long-term experiment on highly sodic soil (pH 10.6), Singh et al. (2008) reported a total biomass ranging from 19.2 Mg ha^{-1} in *Azadirachta indica* to 56.5 Mg ha-^{1} in *P. juliflora* after 10 years of plantations. Other species *A. nilotica*, *Casuarina equisetifolia*, *Terminalia arjuna*, *Pithecellobium dulce*, *Eucalyptus tereticornis*, *Prosopis alba*, *Pongamia pinnata*, and *Cassia siamea* produced aboveground biomass of 50.8, 42.1, 41.6, 32.3, 30.6, 27.8, 26.7, and 21.7 Mg ha^{-1}, respectively. When harvested after 14 years, maximum bole biomass was obtained from *Eucalyptus tereticornis* (231 kg per plant) followed by *A. nilotica* (217 kg), *P. juliflora* (208), and *C. equesitifolia* (197 kg per plant), whereas other species ranged between 52 and 133 kg per plant. The organic carbon ranged from 2.4 to 4.3 g kg^{-1} against 0.8 g kg^{-1} initial contents. The forage biomass of grasses such as *Leptochloa fusca* under trees system produces 16–-18 Mg ha^{-1} annual fresh biomass. Under *P. juliflora-L. fusca*, silvopastoral system soil pH reduced from 10.6 to 8.9; organic carbon increased from 0.18 to 0.58%; and NPK contents also increased significantly after 6 years of establishment. *Brachiaria mutica*, *Chloris gayana*, *Panicum laevifolium*, *P. antidotale*, and *Sporobolu*s spp. are other potential grasses of sodic soils. Kaur et al. (2002a, b) reported carbon storage in different compartments of different silvopastoral systems and found a significant relationship between microbial biomass carbon and plant biomass carbon ($r = 0.92$; $p = 0.01$). Thus, silvopastoral system is the most potential system in sodic soils in terms of biomass (timber, fuelwood, and forage) production, amelioration of soil, and carbon sequestration (for further details see Dagar 2014).

Based on a very important long-term study on saline soils, Tomar et al. (1998) reported that 9-year-old plantations of *P. juliflora* and *C. equesitifolia* produced 96–98 Mg ha^{-1} aboveground biomass when planted with sub-surface and furrow planting methods. Other species which performed well include *Acacia nilotica* (52–67 Mg ha^{-1}) and *A. tortilis* with 41 Mg ha^{-1} biomass. Many grasses such as *Leptochloa fusca*, *Aeluropus lagopoides*, *Dichanthium annulatum*, *Eragrostis* spp., *Panicum laevifolium*, *Brachiaria mutica*, and *Sporobolus* spp. and salt bushes such as *Atriplex*, *Kochia*, and *Salvadora* may form potential agroforestry systems for these soils.

In waterlogged areas, Eucalyptus has been found the most efficient tree for lowering down of water table and generating income in farmers' fields along irrigation canals. In one study, Jeet-Ram et al. (2011) observed that when cloned *Eucalyptus tereticornis* was raised in pair-rows on ridges of acre line in a space of 1 m $\times$ 1 m (density of 300 plants per ha), after a period of 5 years and 4 months, 240 surviving trees were harvested and recorded 24 Mg ha^{-1} (timber 22.1, twigs and leaves 1.1, and fuelwood 0.8 Mg ha^{-1}) aboveground and 8.9 Mg ha^{-1} belowground biomass with a total carbon content of 15.47 Mg ha^{-1}. The farmers got three times higher yield of rice and wheat as compared to those who did not plant trees. At same site, Dagar et al. (2016a) reported 33.2 Mg wood biomass per ha in cloned *E. tereticornis* sequestering 15.2 Mg C ha^{-1}after 6 years of growth, and when planted in block in a space of 4 m $\times$ 2 m, a biomass of 154 Mg ha^{-1}was observed which was equivalent to 66.5 Mg C ha^{-1}. This shows the potential of *Eucalyptus* for carbon sequestration and income generation in a short period from highly degraded waterlogged ecologies.

In a long-term study on calcareous soil in dry region of northwestern India, Tomar et al. (2003) established many tree and grass species using saline water of EC 8–10 dS m^{-1}. After 8 years of planting, the highest shoot biomass was harvested from *Tamarix articulata* (71.9 Mg ha^{-1}) followed by *Acacia nilotica* (23.4 Mg ha^{-1}), *P. juliflora* (20.2 Mg ha^{-1}), and *Eucalyptus tereticornis* (14.8 Mg ha^{-1}). After 16 years of growth, these trees produced 206, 197, 110, and 57 Mg ha^{-1} biomass, respectively. *Cassia siamea*, *Acacia tortilis*, and *Azadirachta indica* produced 94, 87, and 67 Mg ha^{-1}biomass because of their higher survival rate (Dagar 2014). Among grasses, *Panicum laevifolium*, *P. antidotale*, *Cenchrus ciliaris*, *C. setigerus*, *Brachiaria mutica*, and *Dichanthium annulatum* are most successful and potential grasses which can be cultivated irrigating with saline water. These give fodder in sufficient quantity during lean period when people in dry regions go nomadic in search of forage for their cattle. *Aegle marmelos*, *Carissa carandas*, *Emblica officinalis*, *Feronia limonia*, and *Ziziphus mauritiana* are most suitable trees along with low water requiring crops such as barley and mustard during winter season and pearl millet and cluster bean during rainy season (Dagar et al. 2016b). These systems are highly potential in terms of income generation, carbon sequestration, and mitigating climate change.

11.5 Quantification of Carbon Sequestration Potential at Regional Level

Quantification of carbon sequestration potential at regional level in India, ICAR-Central Agroforestry Research Institute, Jhansi, has been working on climate change since 2010–2011 as partner institute of National Innovations in Climate Resilient Agriculture (NICRA). Quantification of carbon sequestration potential (CSP) in agroforestry system has been completed in 17 states, namely, Karnataka, Odisha, Bihar, Andhra Pradesh, Maharashtra, Himachal Pradesh, Tamil Nadu, Madhya Pradesh, Uttar Pradesh, Punjab, Haryana, West Bengal, Chhattisgarh, Rajasthan, Gujarat, Telangana, and Jharkhand covering 58 districts. The carbon sequestration potential of agroforestry system existing on farmers' field was studied under NICRA project in various district of Indo-Gangetic Plains, for which a field survey was conducted through transect walk in the districts. A sample of 20% villages per block and 20% blocks per districts was selected for the survey. The village head/local farmers/village youth were associated for field survey to have a clear picture of the village. The number and length of transect was decided according to area of a particular village. Generally, 1000 m transect line with 10 m × 10 m quadrate at every 100 m was set out to record tree species, number of trees in per unit area (tree density), diameter at breast height (dbh), soil type, crops, etc. In this way the data was generated on number of tree species, tree density, and dbh of tree of a particular village. The data were compiled at block and district level. The biomass, carbon (C) stock, and carbon sequestered were estimated using carbon accounting model (CO2FIX v3.1 model) developed as part of the Carbon Accounting in Forest Ecosystem (CASFOR II), project, Wageningen, the Netherlands.

The carbon sequestration potential of agroforestry system depends upon the tree species, tree density, management practice, and climatic condition. Overall, the tree density in agroforestry system in different states is about 17.8 trees ha^{-1}. The maximum tree density (41 trees ha^{-1}) is recorded in Maharashtra followed by Andhra Pradesh and Himachal Pradesh (Fig. 11.2). The composition of tree species at country level indicates that the population of medium-growing trees are more (9.12 trees ha^{-1}) as compared to fast-growing trees (6.40 trees ha^{-1}). The population of slow-growing trees at country level is 2.24 trees ha^{-1} (Newaj et al. 2018).

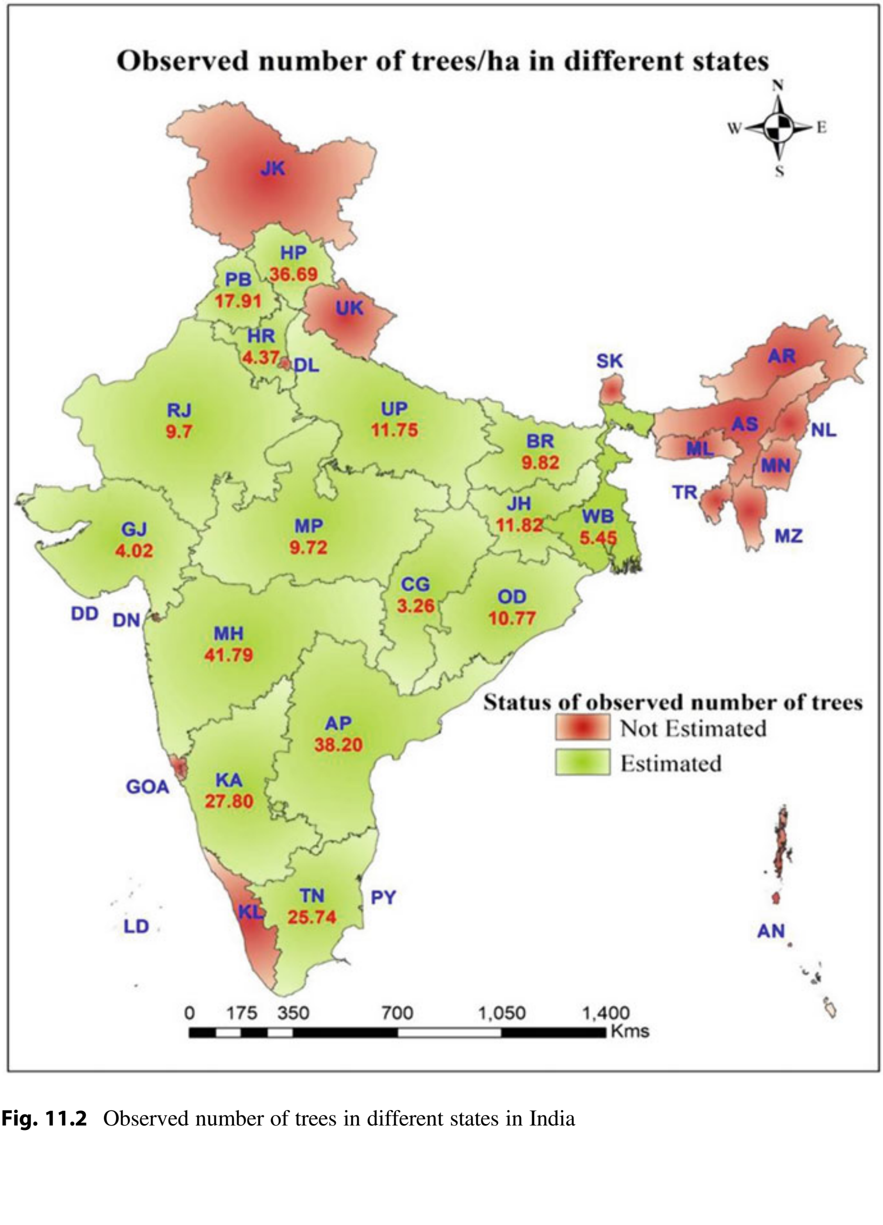

Fig. 11.2 Observed number of trees in different states in India

Table 11.3 Carbon sequestration potential (CSP) of agroforestry systems existing on farmers' fields in different states of India

State (No. of district)	Total C stock in baseline (Mg C ha^{-1})	Net C-sequestered oversimulated period of 30 years (Mg C ha^{-1})	CSP (Mg C ha^{-1} yr^{-1})
Uttar Pradesh	15.15	7.19	0.25
Gujarat	20.26	3.29	0.11
Bihar	15.28	7.51	0.22
West Bengal	14.35	3.68	0.12
Rajasthan	22.29	7.05	0.49
Punjab	17.32	7.71	0.25
Haryana	15.19	2.69	0.09
Himachal Pradesh	33.48	28.36	0.65
Maharashtra	27.70	28.95	0.82
Madhya Pradesh	21.24	5.54	0.18
Karnataka	28.36	10.55	0.35
Tamil Nadu	24.50	17.95	0.60
Andhra Pradesh	20.97	20.80	0.69
Telangana	21.76	13.93	0.46
Odisha	24.42	7.50	0.25
Chhattisgarh	16.59	3.07	0.19
Jharkhand	16.38	5.24	0.17
Mean	**22.97**	**11.35**	**0.35**

Source: ICAR-CAFRI annual report (2017–2018)

Carbon sequestration potential of agroforestry systems, mainly influenced by the climatic condition of particular district or states, tree density, and nature of tree species, and management practices are involved in cultivation of trees and or crops. Data on total biomass, soil carbon, and biomass carbon of agroforestry systems in different districts of a particular state are given in Table 11.3, which clearly showed that amount of carbon sequestered in agroforestry system is having positive correlation in most of the cases, but somewhere nature of tree species like slow-growing, medium-growing, and fast-growing trees is also reflected in amount of carbon sequestered.

Total carbon stock under baseline in different states of the country varied from 14.5 to 33.48 Mg C ha^{-1}. The maximum carbon stock in agroforestry is available in Himachal Pradesh followed by Karnataka, Maharashtra, Tamil Nadu, and Rajasthan. The net carbon sequestered oversimulated period of 30 years is almost equal in Maharashtra and Himachal Pradesh, but Chhattisgarh has sequestered lowest amount carbon after a period of 30 years. Carbon sequestration potential in agroforestry system existing on farmer's field varied from 0.11 to 0.82 Mg C ha^{-1} yr^{-1} in these states. The maximum CSP of agroforestry systems is observed in Maharashtra followed by Andhra Pradesh and Himachal Pradesh (Table 11.3 and Fig. 11.3).

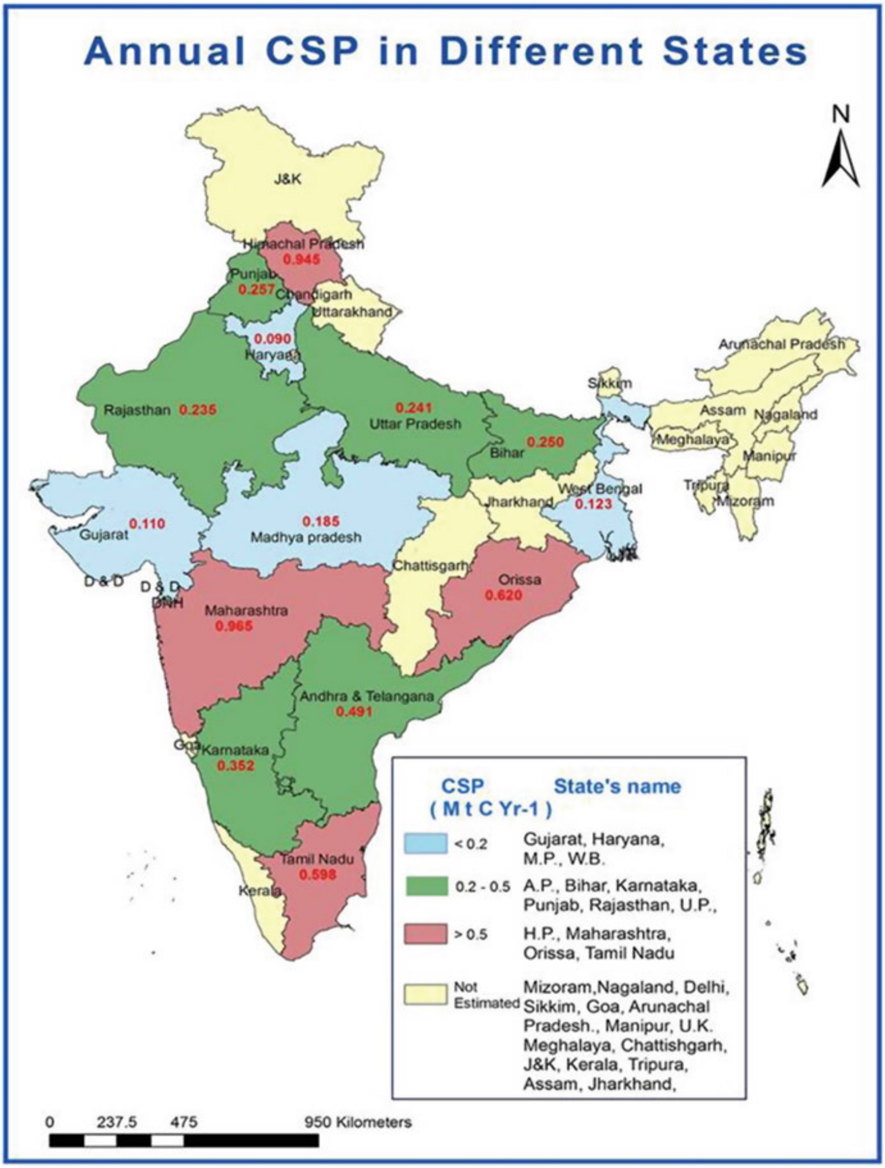

Fig. 11.3 Carbon sequestration potential in different states of India

Carbon sequestration potential of agroforestry systems existing on farmers field in some of the districts from Haryana, Gujarat, Uttar Pradesh, and Rajasthan, in which the land is suffering from various type of land degradation like desertification and salinity/alkalinity, and the number of trees, biomass, biomass carbon, soil carbon, and carbon sequestration potential of agroforestry system are given in following table, which clearly shows that tree density plays an important role in carbon sequestration, but sometimes nature of tree also plays significant role in carbon sequestration (Table 11.4a–d).

11.6 Case Studies of Carbon Sequestration in Agroforestry Systems

11.6.1 Case I: Study from Kullu District, Himachal Pradesh, India (Rajput et al. 2017)

This study was comprised of four mountainous ranges having altitudinal ranges of 1100–2300 m a.s.l. Each range was then further divided into four altitudinal gradients, viz., 1100–1400, 1400–1700, 1700–2000, and 2000–2300 m a.s.l. In each altitudinal range, five land use systems, viz., agriculture, agro-horticulture, horticulture, silvo-pasture, and forests were selected. This experiment was laid out as randomized block design (factorial experiment), comprising 20 treatment combinations [5 (land use systems) × 4 (altitudinal ranges)] having specific tree-crop combinations. The results revealed that maximum total biomass of 404.35 Mg C ha^{-1} was accumulated by forest land use and followed a decreasing trend in the order as forest > silvo-pasture > agro-horticulture > horticulture > agriculture. Biomass and carbon density potential enhanced with the increase in the altitudinal ranges from 1100–1400 to 2000–2300 m a.s.l; but, the rate of C sequestration potential enhanced from 1100 to 2000 m and declined at 2000–2300 m a.s.l. Maximum carbon density (393.29 Mg C ha^{-1}) of both plant and soil was displayed by the forest-based land use systems situated at an altitudinal gradient of 2000–2300 m a.s.l. Thus, there is ample scope of carbon sequestration in agroforestry system in fragile the Himalayan ecosystem.

11.6.2 Case II: Study from Kupwara District of Kashmir Valley in India (Ajit et al. 2017)

In this study, Dynamic CO_2 Fix model was used to estimate carbon stock and sequestration potential outside the forest area. Primary survey results revealed that on an average, there were about 135 trees per hectare, existing on farmers' fields. Species of *Malus* (33.75%), *Populus* (29.91%), *Salix* (14.32%), *Juglans* (6.68%), and *Robinia* (4.7%) were dominant tree species. Paddy and maize were the dominant *kharif* crops, whereas *rabi* (winter) season was dominated by oilseeds and fodder crops. The carbon sequestration potential in all the three pools simultaneously (viz., tree, crop, and soil) of existing agroforestry systems (AFS) was predicted as 0.88 Mg C ha^{-1} yr^{-1}. AFS at district level were estimated to sequester 146,996 Mg of CO_2 equivalent annually, which may offset completely the greenhouse gas emissions from agriculture/irrigation sector on account of electricity consumption throughout the state of Jammu and Kashmir.

Table 11.4 (a-d) Carbon sequestration potential of agroforestry systems existing on farmers' fields under different districts of various states

(a)							
Parameter			Rajasthan				
Districts (number of trees)[a]			Jhunjhunu (6.95)	Sikar (12.42)	Pali (14.90)	Dausa (12.87)	Bikaner (1.40)
Tree biomass (above and below ground) in Mg DM ha^{-1}	Baseline	Biomass	4.33	7.62	11.25	11.01	0.86
	Simulated		10.04	18.74	33	28.59	2.87
Total biomass (tree + crop) in Mg DM ha^{-1}	Baseline		17.13	19.19	17.19	12.88	2.22
	Simulated		23.2	30.64	39.11	30.51	4.27
Soil carbon (Mg C ha^{-1})	Baseline	Carbon	4.51	4.28	16.5	16.49	8.00
	Simulated		8.48	7.34	16.92	17.01	11.34
Biomass carbon (Mg C ha^{-1})	Baseline		7.58	8.64	7.95	6.09	1.0
	Simulated		10.48	14.11	18.47	14.55	1.98
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline		12.09	12.92	24.45	22.58	9.0
	Simulated		18.96	21.45	35.39	31.56	13.32
Net carbon sequestered over the simulated period of 30 years (Mg C ha^{-1})		Carbon sequestered	6.87	8.53	10.94	8.98	4.32
Estimated annual carbon sequestration potential (Mg C ha^{-1} yr^{-1})			0.22	0.28	0.36	0.29	0.14

(b)

Parameters			Haryana (number of trees[a]) Hisar (2.17)	Kurukshetra (6.59)
Tree biomass (above and below around) Mg DM ha^{-1}	Baseline	Biomass	0.78	0.97
	Simulated		2.40	3.00
Total biomass (tree + crop) Mg DM ha^{-1}	Baseline		17.54	7.96
	Simulated		19.63	10.18
Soil carbon(Mg C ha^{-1})	Baseline	Carbon	10.31	9.1
	Simulated		12.89	9.75
Biomass carbon(Mg C ha^{-1})	Baseline		7.58	3.48
	Simulated		8.57	4.53
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline		17.89	12.49
	Simulated		21.46	14.28
Net carbon sequestered over the simulated period of 30 years (Mg C ha^{-1})		C-sequestered	3.57	1.80
Estimated annual carbon sequestration potential (Mg C ha^{-1} yr^{-1})			0.12	0.06

(c)

Parameters			Gujarat (number of trees per ha[a])				
			Dahod (7.11)	Junagrah (2.07)	Patan (1.81)	Banaskantha (4.32)	Anand (4.85)
Tree biomass (above and below ground) (Mg DM ha^{-1})	Baseline	Biomass	3.43	1.30	1.58	3.74	3.02
	Simulated		4.92	4.36	2.16	9.30	8.00
Total biomass (tree + crop) (Mg DM ha^{-1})	Baseline		5.63	8.50	6.84	19.24	6.85
	Simulated		7.18	11.77	7.57	25.24	11.94
Soil carbon (Mg C ha^{-1})	Baseline	Carbon	24.13	23.38	10.02	11.11	11.75
	Simulated		29.66	23.49	11.17	12.64	12.03
Biomass carbon (Mg C ha^{-1})	Baseline		2.60	3.73	3.02	8.47	3.10
	Simulated		3.33	5.28	3.37	11.31	5.52
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline		26.73	27.11	13.04	19.58	14.85
	Simulated		32.99	28.77	14.54	23.95	17.55
Net carbon sequestered over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	6.26	1.61	1.50	4.37	2.70
Estimated annual carbon sequestration potential (Mg C ha^{-1} yr^{-1})			0.21	0.06	0.05	0.14	0.09

(d)

Parameter			Uttar Pradesh (number of trees[a])				
			Sultanpur (6.14)	Bulandshahr (7.01)	Gorakhpur (15.78)	Mirzapur (10.00)	Faizabad (19.94)
Tree biomass (above and below ground) (Mg DM ha^{-1})	Baseline	Biomass	2.56	2.71	18.20	8.68	15.50
	Simulated		8.24	8.65	31.66	20.45	31.45
Total biomass (tree+ crop) in (Mg DM ha^{-1})	Baseline		11.14	6.95	19.66	12.38	*44.44*
	Simulated		17.05	13.20	34.5	24.28	*61.20*
Soil carbon (Mg C ha^{-1})	Baseline	Carbon	8.13	10.65	9.89	13.76	4.60
	Simulated		8.63	11.26	11.01	14.45	*11.17*
Biomass carbon (Mg C ha^{-1})	Baseline		4.92	3.11	9.30	4.17	*19.90*
	Simulated		7.75	6.11	16.41	9.82	*27.87*
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline		13.05	13.76	19.19	5.25	*24.50*
	Simulated		16.38	17.37	27.42	11.47	*39.04*
Net carbon sequestered over the simulated period of 30 years (Mg C ha^{-1})		Carbon sequestered	3.33	3.61	8.23	8.23	14.54
Estimated annual carbon sequestration potential (Mg C ha^{-1} yr^{-1})			0.11	0.12	0.32	0.32	0.48

Source: ICAR-CAFRI annual report (2017–2018)
[a]Values in parenthesis are number of trees

11.6.3 Case III: Role of Agroforestry in Mitigation of Climate Change in India (Ram Newaj et al. 2018)

ICAR, Central Agroforestry Research Institute, Jhansi, has been working since 2011 as one of the partners of NICRA project on "Carbon sequestration potential of agroforestry systems in India." Under this project a program is designed for mapping of agroforestry area in the country and their assessment of carbon sequestration potential of agroforestry systems existing on farmers' fields at country level. Assessment of carbon sequestration has been completed in 16 states covering 51 districts (Uttar Pradesh, Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, Madhya Pradesh, Chhattisgarh, Orissa, and Telangana), and mapping of agroforestry area is also completed in 10 agro-climatic zones out of 15 zones of the country. Initially, area estimation of agroforestry has been done based on tree cover (minimum 10% tree cover is set as threshold for agroforestry), and in this way area under agroforestry comes out to be 17.45 million hectare. This is a preliminary estimate, and after completing the mapping in rest of the five agro-climatic zones, the real estimate of area under agroforestry will be known. Tree biomass (above- and belowground), net carbon sequestered oversimulated period of 30 years, and CSP is extrapolated at country level based on 51 districts' data across the 16 states.

In this way, total tree population in agroforestry at country level is estimated to be 321.45 million trees with 17.45 million ha area under agroforestry. Tree biomass available in agroforestry was assessed to be 9.61 Mg per hectare, and the total biomass of trees (dry mass) under agroforestry systems at country level has been assessed to be 167.69 million Mg. Carbon sequestration potential (CSP) of agroforestry systems existing on farmers' fields was found to be 0.35 Mg C ha^{-1} yr^{-1}. Looking to the area under agroforestry (17.45 million ha) in the country, the total carbon stock will be 6.10 million Mg, and CO_2 equivalent C will be 22.41 million Mg. In this way the agroforestry can offset 22.41 Mg CO_2 of total CO_2 equivalent GHG emission (1831.64 million Mg) in the country (Table 11.5).

Table 11.5 Role of agroforestry to offset CO_2 in total CO_2 equivalent GHG emission (1831.64 million Mg)

Land use (area) (A)	Carbon sequestration potential Mg C ha^{-1} yr^{-1} (B)	Total CSP potential million Mg C C = (A × B)	CO_2 eq. million Mg D = (C × 3.67)	Contribution in total GHG emission (%)
Agroforestry (17.45 million ha)	0.35	6.10	22.41	1.22
Forest (69.16 million ha)[a]	274725.27	19.0[a]	69.73	3.80

[a]Indian States of forest research carbon stock in Indian forests (2017)

11.7 Conclusion

Globally, agroforestry is now well-accepted strategy to tackle the climate change. India is endowed with traditional agroforestry systems, where farmers willingly maintain trees on their farms to secure livelihood. There are evidences of better carbon capture and sequestration potential under different agroforestry systems irrespective of indigenous or managed agroforestry systems. It's high time to consider the benefits accrued through adoption of agroforestry systems in terms of mitigation and adaptation in the scenario of climate change. Keeping this in view, the ICAR-CAFRI, Jhansi, undertook a mega project on carbon sequestration in different agroforestry systems and came out with total biomass and carbon stock existing in these systems and the area covered by these systems. The recorded total carbon stock from existing agroforestry was found to be 6.10 million tones C and 22.41 million tones CO_2 equivalent from 17.45 million ha agroforestry area. However, some knowledge gaps concerning C sequestration in AFS could be identified as (1) quantitative assessment of carbon inputs and stocks in various components of AF systems, 2) analysis of deep soil carbon storage and its dependence on tree species and their age, and (3) design of agroforestry systems for the optimization of the area allocated to trees and crops within different systems so as to maximize C sequestration. There is no doubt that all AFS have tremendous potential in all the agro-ecological zones of India to sequester carbon, which in turn helps in mitigating adverse effects of climate change.

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Sustainability of *Faidherbia albida*-Based Agroforestry in Crop Production and Maintaining Soil Health

12

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Abstract

Faidherbia (*Faidherbia albida*), previously known as *Acacia albida*, is a leguminous woody tree widely distributed throughout Africa and the Middle East. This species plays a critical role in both crop and animal production systems, and because of its unique phenology, it is considered an ideal agroforestry species in Africa. Although the effects of *Faidherbia* on soil properties and crop yields have been the subject of several decades of research, there is still a dearth of information on the sustainability of *Faidherbia*-based traditional and new agroforestry practices. In this review, we applied the sustainable intensification (SI) framework to provide an up-to-date synthesis of the evidence for sustainability of *Faidherbia*-based agroforestry in sub-Saharan Africa. The analysis of SI indicators suggests the sustainability of *Faidherbia*-based agroforestry systems in terms of productivity, human well-being and economic and

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environmental sustainability. Maize and sorghum productivity were increased by 150 and 73% under the canopy compared to the open area, respectively. In 96% of the cases, soil organic carbon was found to increases under the canopy relative to the open area. The tree adds significant amounts of nutrients to soil, thus improving the growing conditions for crops.

Keywords

Indicator · Land degradation · Parklands · Sustainable intensification

12.1 Introduction

Faidherbia albida Del., previously known as *Acacia albida*, is a leguminous woody tree species, belonging to the family Fabaceae, subfamily *Mimosoideae*. For brevity, we will refer to this species as *Faidherbia* in the rest of this paper. This species is widely distributed throughout Africa and the Middle East, including Israel, Lebanon, Oman, Palestine, Saudi Arabia, Syria and Yemen (Barnes and Fagg 2003; Boffa 1999). In its native range, *Faidherbia* is adapted to a wide range of soils and altitudes, ranging from 270 m below sea level in Palestine to over 2500 m in Sudan (Barnes and Fagg 2003) and Ethiopia (Hadgu et al. 2009). In Africa, its natural distribution does not appear to follow clear-cut climatic zones, but it is commonly found in river valleys and along lakeshore plains (Barnes and Fagg 2003).

In the African continent, Faidherbia plays a key role in both crop and animal production systems. It is an ideal agroforestry species because it avoids competition with crops for light by shedding its leaves during the wet season and growing them anew in the long dry season, a phenomenon termed reverse phenology. Unlike other trees, Faidherbia remains leafless during the wet season, and thus, it hardly competes with crops for light and water, while it provides a microclimate favourable for growing crops (Barnes and Fagg 2003; Boffa 1999). The tree's presence in crop fields has been shown to increase yields, a phenomenon termed the "albida effect" (Boffa 1999). This has been variously attributed to improved soil physical and chemical properties (Barnes and Fagg 2003; Depommier et al. 1991), reduced soil and air temperatures (Vandenbeldt and Williams, 1992), symbiosis with rhizobium and arbuscular mycorrhizal fungi (Barnes and Fagg 2003), supporting termite activity (Brouwer et al. 1991), and improved nutrient recycling (Charreau and Videl 1965). In a study in Ethiopia, wheat production under unpruned Faidherbia tree was much higher than productivity under pruned Faidherbia tree. This is attributed to improved CO_2 assimilation rate of wheat as a result of temperature stress reduction.

The green leaves of Faidherbia are also rich in protein and carbohydrates, providing a valuable fodder for livestock during the dry season (Barnes and Fagg 2003; Boffa 1999). The total protein content in leaves, pods and seeds has been reported in the range of 150–260 g kg^{-1} of dry matter, with digestibility as high as 73%. In West Africa, pods are collected and fed to animals or sold in markets as animal feed. Pods fall towards the end of the dry season during the months of March to April, and these are fed to livestock when other fodder is scarce. The average pod production is 6–135 kg tree^{-1} year^{-1} in the Sudanian zone. In the Mana woodland in Zimbabwe, pod production was 590 kg ha^{-1} year^{-1} at 11 tree ha^{-1} (Barnes and Fagg 2003). People also eat the seeds, the bark is used for traditional medicines, while its flowers supply honeybees with nectar (Mokgolodi et al. 2011).

Crop yield improvement is the most important benefit of Faidherbia-based agroforestry systems. Additional benefits include fodder and fuelwood. The effects of Faidherbia on soil properties and crop yields have been the subject of several decades of research, and there is now a growing body of evidence showing its role in crop production and maintaining soil health. Much of this has been synthesized through recent meta-analysis (e.g. Bayala et al. 2012; Sileshi 2016). However, there is still a dearth of information on the sustainability of traditional and new Faidherbia-based agroforestry practices. Therefore, the objective of this paper was to provide an up-to-date synthesis of the evidence for sustainability of Faidherbia-based agroforestry practices in sub-Saharan Africa (SSA). Through a literature review of recent developments the sustainable intensification framework, case studies and meta-analyses of published data, this synthesis attempts to create a better understanding of the Faidherbia-based agroforestry for developing suitable management strategies that are useful for researchers, development agencies and policymakers.

12.2 Methods

12.2.1 Analytical Framework

Sustainability is a very broad concept encompassing natural, social and economic capital (Bosshard 2000), and it would not be possible to present a single metric applicable to any situation (Smith et al. 2017). The definition of sustainability is also continually evolving. As such, assessing the sustainability of the Faidherbia-agroforestry in the conventional sustainability framework will be a daunting task. Instead, in this analysis, we used indicators of sustainable intensification, which are more relevant to the system being studied. Sustainable intensification (SI hereafter) is defined as producing more output from the same area of land while reducing the negative environmental impacts and, at the same time, increasing contributions to natural capital and the flow of environmental services (Pretty 1997; Pretty et al. 2011). SI is also recognized as one of the cornerstones of climate smart agriculture (Campbell et al. 2014). Therefore, in this analysis, we applied the SI framework and relevant indicators to assess the sustainability of Faidherbia-based agroforestry practices. Since most Faidherbia-based agroforestry practices involve both crop and livestock production, we considered indicators that are relevant to both production systems.

Several indicators of SI are available in the literature, and these fall under five major domains, namely, productivity, environmental sustainability, economic sustainability, social sustainability and human well-being (Smith et al. 2017; Snappa et al. 2018). In this analysis, we selected the most frequently used SI indicators under each domain. Specifically, we focussed on those indicators for which information on Faidherbia-based agroforestry practices was readily available.

The main indicators of productivity in crop and livestock production systems include crop yield, biological inputs, biomass production, crop diversity, fodder production, input efficiency, resilience, water use efficiency and yield variability (Smith et al. 2017). Yield is, by far, one of the most frequently used SI indicators of productivity in the literature (Smith et al. 2017). Yield is indexed by the production of crops per unit of land area (Mg grain ha^{-1}) in crop production systems, while in livestock systems, yield is measured as the production of animal products (milk or meat) per animal per day, or the production of milk per animal per lactation period (Smith et al. 2017). Yield variability, usually indexed by the coefficient of variation (CV) is another important but less frequently used indicator (Smith et al. 2017). For the present analysis, we chose crop yield, yield variability and fodder yield and used the CV as a measure of production risk; a larger CV reflects more risk. Water use efficiency is also used as a metric of productivity and sustainability in agricultural intensification efforts, particularly in rain-fed smallholder systems (Garrity et al. 2010; Sileshi et al. 2011). Water use efficiency measures include grain yield mm^{-1} of rainfall (Smith et al. 2017).

The most frequently cited indicators of environmental sustainability are soil quality, biodiversity, carbon sequestration, greenhouse gas (GHG) emission and erosion control. Soil quality, generally, refers to the capacity of the soil to support and sustain agricultural production, and it is used as the main indicator of soil health (Barrios et al. 2012). Sometimes, soil quality and soil health are used interchangeably. However, soil health is broader than soil quality (Barrios et al. 2012), and it is defined as an integrative property that reflects the capacity of soil to respond to agricultural interventions, so that it continues to support both agricultural production and the provision of other ecosystem services (Kibblewhite et al. 2008). In this review, we will use indicators of soil quality. One of the most commonly employed metrics of soil quality is soil organic matter (SOM) or the closely related metric soil organic carbon (SOC). An increasing global consensus exists on the critical importance of SOC to support soil health and the provision of multiple ecosystem services. SOC storage and C sequestration are important indicators of the climate change mitigation potential of agricultural ecosystem. Other chemical properties that are often used as metrics of soil nutrient status include total soil N, extractable P, K, Ca and Mg, cation exchange capacity, and pH (Smith et al. 2017; Snappa et al. 2018). In this analysis, we used SOC, total N, extractable P, K, Ca and Mg and pH. Biodiversity is measured on the farm or in the surrounding landscape using biodiversity indices (Smith et al. 2017). Metrics of erosion, generally, focus on the field or at farm level, with the rate of erosion expressed in tons (Mg) of soil lost ha^{-1} $year^{-1}$.

To judge economic sustainability, a number of indicators have been suggested, but agricultural income, labour productivity and input access are the most frequently used indicators in the SI literature (Smith et al. 2017). In this review, we used agricultural income measured as net income (i.e. income from agriculture minus agricultural expenses).

Among the indicators of human well-being, the most important ones are food safety, food and nutrition security, labour saving and risk reduction (Smith et al. 2017). Risk is generally measured as either production risk or perceived risk. Production risk can be quantified as the probability that crops will produce sufficient yield to meet the food or nutritional needs of the household. In this analysis, we mainly used food and nutrition security and production risk, but labour saving to a lesser degree due to unavailability of data. In order to judge production risk, we compared maize yields under canopy with yields in the open area using the probability of achieving the African Green Revolution grain yield target of 3 Mg ha^{-1}, which is cited as the minimum yield required for achieving food self-sufficiency in SSA (Sánchez 2015).

In order to evaluate the selected indicators relating to soil fertility, agricultural productivity, economic sustainability and human well-being, we have used literature review, meta-analysis and case studies.

12.2.2 Literature Review and Data Collection

A review of the literature was undertaken to identify Faidherbia-based agroforestry practices mainly in Africa and the influence of the tree on soil, crop and animal productivity. Data on soil nutrients and crop yields were assembled from both the published and unpublished literature to conduct meta-analyses. In order to satisfy the requirements of meta-analysis, the selection and inclusion of studies were based on the following criteria. For a study to be included in the analysis, it must: (1) have soil or crop yield measurements under the canopy and a corresponding measurement in the open area or outside canopy, (2) have reported the values as numerical data and (3) reported soil properties for clearly defined soil depths.

From the studies thus, selected, pairs of observations (under canopy and corresponding values in the open area) on soil organic matter (SOM) and/or soil organic carbon (SOC), total nitrogen (N), extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and pH, and crop yields or plant dry matter were extracted. The extraction of soil data was restricted only to the top 30 cm soil depth because 90% of crop roots in drylands are known to be concentrated in this depth. All SOM data were converted to SOC by dividing SOM by a factor of 2 as proposed by Pribyl (2010).

12.2.3 Meta-Analyses

In order to facilitate the meta-analyses, the response ratio (RR) was calculated as the ratio of measurements under the canopy (U) to the open area (O) for each response variables (i.e. SOC; total N; extractable P, K, Ca and Mg; pH; and yields of maize, sorghum and groundnut). The expected values of the effect sizes (i.e. RR = U/O) were estimated using linear mixed effects models with site productivity used as a fixed effect and study as a random effect. Here, the productivity of a site was judged as "low" when soil nutrient content or crop yield is below the average value for the open area. Conversely, productivity was judged as "high" when soil nutrient content or crop yield is above-average in the open area across studies. Statistical inference was based on robust estimates of RR and their 95% confidence intervals (95% CI).

In addition, the variation in the effect sizes with distance from the tree trunk was explored using an exponential distance-decay model (EDDM). In an unconstrained system, the EDDM has the following form:

$$\mathrm{RES}_z = \alpha e^{-\beta D_z}$$

where RES = response variable, D = distance, e = base of the natural logarithm, α = intercept and β = slope.

The model was fitted to data on SOC, total N, extractable P, K, Ca and Mg, and yields of maize, millet and sorghum, and the agreement between observations and model predictions were statistically tested. Model parameters were estimated using a Bayesian approach, where the model parameters are treated as random variables, and inference about parameters was based on their posterior distributions, given the data. The estimation uses a Markov Chain Monte Carlo (MCMC) simulation by Gibbs sampling to simulate samples from posterior distributions. The maximum likelihood estimates of the parameters α and β were used as the starting values for the simulation. Then, the parameters and their 95% credible interval were estimated through MCMC. If the magnitude of Faidherbia influence decreases monotonically with distance, β will be negative and the 95% credible interval of β will not include 0 or positive values. Where this condition was satisfied, it was taken as a clear evidence of predictable spatial patterns created by Faidherbia.

12.2.4 Case Studies

In addition to the review and meta-analyses, specific case studies were used to highlight the sustainability of Faidherbia-based agroforestry practices. One of the case studies chosen focussed on farmers' evaluation of the benefits of Faidherbia-based agroforestry (Hadgu et al. 2011). In that study, a total of 115 farmers were randomly selected from different altitudinal zones of Northern (Tigray), central (East Shoa) and eastern (Eastern Hararghe) Ethiopia for interviews and observations of their farms. The sites in central Ethiopia were located at low altitudes (<1500 masl), where Faidherbia occurs in parklands. In eastern Ethiopia, the sites were located at mid-altitude ranges (1500–2000 masl), while in Northern Ethiopia, the sites were located at high-altitude zone (>2000 masl). In addition to the sample farmers, key informants who practiced Faidherbia-based farming compared with others in the sample villages were also included in the survey.

12.3 Synthesis

12.3.1 Typology of Faidherbia-Based Agroforestry Practices

12.3.1.1 Agroforestry Parklands

Agroforestry parklands are common in the semi-arid or subhumid tropics in West Africa, Central Africa, East Africa (Bayala et al. 2014; Boffa 1999; Teklehaimanot 2004), Southern Africa (Campbell et al. 1991) and North Africa (Raison 1988). The parklands of the Sahelian West Africa traverse more than 15 countries that share a similar ecology, climate and agroecology (Asse 2007). Agroforestry parklands exemplify complex social-ecological systems currently threatened by environmental degradation, and climatic and social changes (Asse 2007). For example, the Sahel Zone is a dryland ecosystem characterized by subsistence agriculture producing cereals, notably sorghum and millet, often on degraded soils. The vulnerability of this zone to droughts and soil degradation makes intensive farming practices risky (Bayala et al. 2012).

While parkland ecosystems look like savannas (Boffa 1999), recent studies suggest that they mainly constitute an anthropogenic vegetation assemblage (Maranz 2009), which is a reflection of a slow process of species selection and density management of indigenous trees by farmers (Mortimore and Turner 2005; Rhoades 1997; Teklehaimanot 2004). According to Bayala (2014), parklands reduce the risk of climate change to smallholders in SSA through microclimate regulation. The trees also buffer crops against extreme heat and provide an affordable climate-smart production option (Sida et al. 2018a).

In some parklands, Faidherbia is the most common tree species (Boffa 1999). Parkland agroforestry systems dominated by scattered Faidherbia trees are particularly common across the Sudano-Sahelian zone of SSA (Sida et al. 2018b). In the humid and subhumid areas such as the Ethiopian highlands, scattered trees of Faidherbia occur on cropland. Tree densities in this agroforestry arrangements are usually low (Table 12.1) but much higher than parklands. A variety of crops are grown under these low-density stands of mature trees (Table 12.1). For example, in the Central Rift Valley of Ethiopia, wheat and tef [*Eragrostis tef* (Zucc.) Trotter] are grown under low density (4.2 trees ha^{-1}) of mature Faidherbia trees (Sida et al. 2018b). In the Hararghe highlands of eastern Ethiopia, cereals (e.g. maize and sorghum), vegetables and coffee are grown under Faidherbia (Poschen 1986; Teketay and Tegineh 1991). Similarly, Hadgu et al. (2009) described a traditional Faidherbia-based agroforestry practice in the Tigray highlands of Northern Ethiopia. In this region, Hadgu et al. (2009) identified three different Faidherbia-based land use systems: (1) Faidherbia present along field boundaries or within fields without interference of other tree species or livestock, (2) Faidherbia and livestock system where the tree is used for shade and fodder, and (3) Faidherbia and *Eucalyptus* system.

Farmers usually protect and intensively manage naturally regenerating trees during tillage operations, thus keeping tree density low so that canopy cover is not continuous. Therefore, in agroforestry parklands, isolated Faidherbia tree stands of

Table 12.1 Density (trees ha^{-1}) range and tree cover (%) of naturally growing Faidherbia trees in different countries in Africa

Country	Region and site	Density	Source
Burkina Faso	Bam province, Mossi	7–45	Depommier et al. (1991)
	Houët Province, Dossi	3–30	Depommier and Detienne (1996)
	Yatenga, Tugu	4	Marchal (1980)
Cameroon	North, village of Tokombéré	5.4	Libert and Eyog Matig (1996)
	North, Maroua	23 (13.5%)	Triboulet (1996)
Côte d'Ivoire	North, village of Dolékaha	3.5	Bernard et al. (1996)
Ethiopia	Debre Zeit, ILRI site	6.5	Kamara and Haque (1992)
	Hararghe highlands, Alemaya	1–10	Poschen (1986)
	Hararghe highlands, Harar town	20 (>33%)	Poschen (1986)
	Central Rift Valley	4.2	Sida et al. (2018b)
	Central Rift Valley, Adulala	5.8	Dilla et al. (2019)
Malawi	Chikombo	28	Phombeya (1999)
	Liwimbi	28	Phombeya (1999)
	Three sites	17.8%	Beedy et al. (2015)
Mali	Inner delta, upland villages	5–10 (<5%)	Gallais (1967)
	Inner delta, bottomland villages	20–25 (15–20%)	Gallais (1967)
	Dogon, Dembéré-Douentza	40–50	Gallais (1965)
Niger	Tilly village on Niger River	4	Moussa et al. (1999)
	Guilleny village	32	Moussa et al. (1999)
	Dosso area, Tibiri-Dogon	29	Montagne (1996)
Senegal	Serer, Bambey area	16	Charreau and Videl (1965)
	Peanut Basin	9	Seyler (1993)
Sudan	Jebel Marra highlands, Koronga	7–20	Miehe (1986)
	Jebel Marra, river terraces	74	Radwanski and Wickens (1967)

Tree cover is given in parentheses. The table is largely adapted from Boffa (1999)

uneven age, height and canopy are found. These trees can have a number of important consequences for ecosystem functioning due to the various interactions between trees, soil fertility and animals. Faidherbia is increasingly being promoted with soil and water conservation practices (Bayala et al. 2012; Larwanou and Saadou 2010; Reij et al. 2009). However, agroforestry parkland especially in the Sahel are rapidly degrading due to a complex combination of natural, technological and socio-economic factors (Teklehaimanot 2004).

Widespread reports of senescing savanna parklands in the Sahel have generated a vigorous debate over whether climate change or severe human and livestock pressure is principally responsible. Recent work indicates that the Sudanian parkland system, which extended in the past to near 15°N, is now not found beyond 13.5°N; the loss of mesic trees being driven by the sharp drop in rainfall since the 1960s (Maranz 2009). While drought itself can lead to tree mortality, drought stress can be a precursor for damage by insects and disease. In some regions, the population of Faidherbia trees is declining due to excessive pruning and livestock damage, which reduce recruitment (Sida et al. 2018b). For example, in the Central Rift Valley of Ethiopia, the current practice involves pruning trees completely every 2–3 years (Sida et al. 2018b). This reduces the seed source and constrains recruitment. The frequent excessive pruning seems to have an impact on the reverse phenology. In the same study area, some trees kept their leaves during the wet season, and eventually this might reduce the positive effects of Faidherbia on crops. In addition, a low juvenile to adult ratio—a manifestation of a population facing an extremely high risk of juvenile mortality—has been reported (Sida et al. 2018b). According to Sida et al. (2018b), unless seed production is increased by decreasing either pruning frequency or intensity, the density of Faidherbia trees is predicted to fall to 1 tree ha^{-1} within a decade. Another threat to the sustainability of the parklands is the lack of tree planting culture. In most cases, farmers depend on naturally regenerated trees.

12.3.1.2 Systematic Planting of Faidherbia on Cropland

Faidherbia is also increasingly being promoted in combating desertification (Kirmse and Norton 1984**),** re-greening of the Sahel (Reij et al. 2009), carbon-offset projects (Plan Vivo 2010) and climate-smart agricultural practices, combining agroforestry with conservation agriculture with trees in Africa (Garrity et al. 2010). In these new agroforestry practices, Faidherbia is planted on cropland in a systematic grid pattern (Sileshi et al. 2014a). For example, the Conservation Farming Unit (CFU) of the Zambia National Farmers Union recommends systematic planting at 10 × 10 m spacing. Over the past decade, the CFU has trained farmers and supplied sufficient seed and sleeves to enable over 160,000 farmers to establish 100 trees annually and to expand their plantings (CFU 2012; Umar et al. 2013). A small-holder cooperative of 19,000 farmers in Eastern Zambia is also encouraging planting of Faidherbia in conservation agriculture fields (Bosco 2012). In addition, close to 2000 outgrower farmers associated with Dunavant cotton in Eastern Zambia receive subsidized inputs for growing Faidherbia in the cotton fields for carbon-offsets (Jack et al. 2015).

The spacing currently used in Faidherbia stands ranges from 3 × 3 m (Dangasuk et al. 1997) to 10 × 10 m (Barnes and Fagg 2003; CFU 2012; Okorio and Maghembe 1994). In some cases, the within-row and between-row spacing are different. For example, Jama and Getahun (1991) used 0.5–3 m within-row and 2–8 m between row spacing in Kenya. In Mozambique, the Plan Vivo recommendation is 10 × 5 m spacing (Plan Vivo 2010).

12.3.2 Sustainability of Faidherbia-Based Agroforestry Practices

12.3.2.1 Productivity

In the crop production systems, our main focus was on the magnitude of increase in yields (in Mg grain ha^{-1}) and their coefficients of variation (CV). In this analysis, maize and sorghum yields were increased by 150 and 73%, respectively, under the canopy compared with the open area. Similarly, barley and wheat yields were significantly increased under the canopy compared with the open area (Hadgu et al. 2009; Desta 2018). Modelling spatial patterns (Sileshi 2016) also revealed a decrease in herbage dry matter and yields of cereal crops, such as barley, wheat, maize, sorghum and millet with increasing distance from the tree trunk. The increase in the productivity of grasses and cereals under the canopy has been attributed to higher soil nutrients, improvement in soil physical properties and microclimate under the tree canopy compared with the open area (Boffa 1999; Sileshi 2016 and references therein).

On the other hand, yields of other crops, such as cotton and groundnut, are either depressed or show no clear patterns. For example, Payne et al. (1998) recorded maximum yields of cotton closer to the drip line than either outside the canopy or closer to the trunk. In the present meta-analysis, groundnut yields were depressed, on average, by 16% under the canopy compared with the open area. The yield depression in groundnuts under the canopy is attributed to increased vegetative growth due to excess N in relation to P and K. The robust estimates of 95% confidence limits (CL) for maize yield increases under Faidherbia canopy over the open area were 1.3–1.8 Mg ha^{-1} across SSA. This was slightly lower than the earlier estimates (2–2.7 Mg ha^{-1}) reported for parklands by Sileshi et al. (2014b). Robust estimates for sorghum yield increases under Faidherbia canopy over the open area were 0.1–0.8 Mg ha^{-1} across SSA. The effects of Faidherbia on maize and sorghum yields were more positive on sites with low productivity compared to inherently productive sites (Sileshi 2016).

In terms of production risks, the CV of maize and sorghum yields were higher in the open area than under the tree canopy, suggesting higher production risks in the open (Table 12.2). The reduction in production risks under Faidherbia canopies is often attributed to moderation of the microclimate in favour of crop plants. Moderation of the soil temperature at the time of seedling establishment is especially an important component of the tree effect. For example, Payne et al. (1998) recorded soil temperature as low as 6 °C under Faidherbia canopies compared to the open area during the day. According to Vandenbeldt and Williams (1992), Faidherbia canopies considerably reduced soil temperatures closer to the optimum for growth of pearl millet. In addition, the spatial variability created by the tree may play a critical role in maintaining ecosystem functioning by concentrating limiting resources under the tree canopy.

Faidherbia has also been reported to increase crop residues (Bayala et al. 2012), which are often used by African farmers to feed animals. However, crop residues usually have low crude protein, phosphorus and calcium contents, but high-fibre and lignin content, which slow digestion and voluntary intake. Faidherbia leaves are rich

Table 12.2 Mean effect of Faidherbia on soil properties and crop yields across SSA and their coefficients of variation (CV)

	Variable	Sample size	Variable	Mean	CV (%)	RR
Soil nutrients	SOC (%)	45	Under canopy	1.8	44.6	1.5[a]
			Open area	1.3	48.2	
	Total N (%)	56	Under canopy	0.5	106.2	1.5[a]
			Open area	0.3	104.0	
	Extractable P	54	Under canopy	28.4	105.9	1.2[a]
			Open area	27.6	108.7	
	Extractable K	45	Under canopy	1.3	138.8	1.3[a]
			Open area	1.1	144.4	
	Extractable Mg	14	Under canopy	3.1	117.9	1.0
			Open area	3.3	130.5	
	Extractable Ca	15	Under canopy	10.6	127.7	1.1
			Open area	10.5	156.9	
	Soil pH	17	Under canopy	6.4	8.2	1.0
			Open area	6.4	8.4	
Crop yield	Maize	119	Under canopy	3.4	66.2	2.5[a]
			Open area	1.7	85.5	
	Sorghum	8	Under canopy	1.4	41.3	1.7[a]
			Open area	1.0	53.5	
	Groundnut	91	Under canopy	1.2	52.8	0.8
			Open area	1.4	47.0	

RR is the response ratio
[a]Indicates significant increases under canopy compared with open area

sources of protein, vitamins and minerals and can be used for supplementing low-quality roughages. Supplementation of barley straw basal diet with 200 g Faidherbia leaf meal increased feed intake and digestibility by sheep (Gebreselassie et al. 2015)

12.3.2.2 Environmental Sustainability

12.3.2.2.1 Soil Quality

The meta-analysis provided clear evidence for the improvement of SOC, N, P and K under Faidherbia canopies over the open area. SOC increased by 46% under Faidherbia canopy compared to the open area (Table 12.2). There was also a 96% probability of overall increase and a 12% probability of doubling in SOC under the canopy relative to the open area. The tree's effect was found to be higher on sites with inherently low SOC than on sites with above-average SOC (Sileshi 2016). SOC influences the capacity of the soil to retain nutrients and water as well as multiple other properties. Increased SOC content, particularly in the light fraction, is known to improve aggregate stability, porosity, hydraulic conductivity and soil structures that resist erosion (Sileshi et al. 2014b).

Like SOC, total N was significantly higher (on average by 50%) under the canopy than in the open area (Table 12.2). The probabilities of simply increasing and doubling of N content under the canopy were 86 and 20%, respectively.

Extractable P and K were also significantly elevated (by 21 and 32%) under the canopy than in the open area (Table 12.2). The probabilities of doubling of soil P or K contents under the canopy were 12 and 8%, respectively (Table 12.2). Extractable Mg and Ca contents and soil pH did not significantly differ between the canopy and the open areas (Table 12.2). The lack of significant differences between the canopy and the open areas in soil pH, Mg and Ca contents is probably due to the small sample sizes. Albeit not being significant, even soil Mg, Ca and pH have over 30% probability of being elevated under Faidherbia canopy relative to the open area. All variables analyzed showed significant decline with distance from the tree bole (Table 12.3), confirming that the tree creats predictable spatial patterns consistent with the distance decay model test here.

The mechanisms by which Faidherbia enriches soil nutrients have been widely debated (Boffa 1999). Barnes and Fagg (2003) have also suggested that the increase under the canopy is a reflection of nutrient mining by the root system from the soil beyond the reach of its crown. The results of this study and finding from studies on related tree species in drylands (e.g. Ludwig et al. 2004) provide more support to the nutrient enrichment hypothesis. The mechanisms for soil enrichment may include deep capture and recycling of nutrients, biological N-fixation (BNF), nutrient subsidy and atmospheric deposition (Dunham 1989; Kamara and Haque 1992; Phombeya 1999; Rhoades 1997; Umar et al. 2013). The nutrients, thus, captured and produced through BNF become inputs on being transferred to the soil via decomposition of litter. This can promote productivity of understorey vegetation, thus leading to build-up of SOC, enrichment in nutrients and improvement in soil physical properties (Sileshi 2016). Nutrient subsidies through bird droppings, animal dung and urine as well as atmospheric deposition may also contribute to improvements in soil nutrients.

These improvements in soil quality have additional environmental benefits, including reduction in fertilizer requirements, greater living soil cover and increased soil biological activity (Yengwe 2011). The environmental benefits of the reduction in fertilizer requirement include energy saved to produce the fertilizer and preservation of water and air quality. Inorganic fertilizer is a source of greenhouse gases (GHGs), particularly nitrous oxide. For example, the use of inorganic fertilizers at the rate of 85 kg N ha^{-1} was estimated to emit, on average, up to 0.6 Mg ha^{-1} of CO_2 equivalent annually. On the other hand, Faidherbia-based agroforestry can increase soil carbon sequestration.

12.3.2.2.2 Biomass Production

The mean above-ground total dry biomass of Faidherbia was estimated at 844 kg tree^{-1} in parklands in the Central Rift Valley of Ethiopia (Dilla et al. 2019). In Malawi, Beedy et al. (2015) estimated above-ground tree biomass of 6.1 Mg ha^{-1} in parklands, varying with site from 3.8–8.7 Mg ha^{-1}. Fuelwood is obtained through pruning of trees or rarely by felling the whole tree. According to Poschen (1986), the

Table 12.3 Bayesian posterior estimate of the slope (β) and its 95% credible interval (95% CI) for the distance-decay model

Measured variables	Country	Site, year	Slope (95% CI)	Source of data analysed
SOC	Ethiopia	Debre Zeit	−0.08 (−0.10, −0.06)	Kamara and Haque (1992)
	Niger	Niamey	−0.03 (−0.04, −0.01)	Payne et al. (1998)
Total N	Ethiopia	Debre Zeit	−0.02 (−0.03, −0.01)	Kamara and Haque (1992)
	Niger	Niamey	−0.03 (−0.04, −0.02)	Payne et al. (1998)
	Nigeria	Maiduguri	−0.12 (−0.19; −0.06)	Verinumbe (1993)
Extractable P	Ethiopia	Debre Zeit	−0.07 (−0.08, −0.05)	Kamara and Haque (1992)
	Niger	Niamey	−0.09 (−0.13, −0.05)	Payne et al. (1998)
	Nigeria	Maiduguri	−0.70 (−0.78, −0.58)	Verinumbe (1993)
Extractable K	Ethiopia	Debre Zeit	−0.14 (−0.18, −0.10)	Kamara and Haque (1992)
	Nigeria	Maiduguri	−0.12 (−0.26, −0.01)	Verinumbe (1993)
Extractable Ca	Nigeria	Maiduguri	−0.15 (−0.27, −0.04)	Verinumbe (1993)
Extractable Mg	Nigeria	Maiduguri	−0.29 (−0.80, +0.25)	Verinumbe (1993)
Maize yield	Malawi	Khombedza	−0.05 (−0.07, −0.03)	Saka et al. (1994)
	Malawi	Mvera	−0.03 (−0.04, −0.03)	Saka et al. (1994)
	Malawi	Bolero 1990	−0.02 (−0.03, −0.01)	Saka et al. (1994)
	Niger	Niyamey, 1991	−0.3 (−0.34, −0.22)	Payne et al. (1998)
	Niger	Niyamey, 1992	−0.24 (−0.30, −0.18)	Payne et al. (1998)
Millet yield	Niger	Niyamey, 1991	−0.10 (−0.13, −0.07)	Payne et al. (1998)
	Niger	Niyamey, 1992	−0.05 (−0.07, −0.03)	Payne et al. (1998)
Sorghum yield	Niger	Niyamey, 1991	−0.29 (−0.33, −0.25)	Payne et al. (1998)
	Niger	Niyamey, 1992	−0.28 (−0.33, −0.22)	Payne et al. (1998)
Sorghum dry matter	Nigeria	Maiduguri	−0.35 (−0.49, −0.21)	Verinumbe (1993)

pruning yields 0.4–0.5 m^3 per mature tree, and most farmers prune once every 4–5 years in Eastern Hararghe region.

12.3.2.2.3 Carbon Sequestration and GHG Mitigation

Faidherbia trees also sequester significant amounts of C both in their woody biomass and in the soil, with a potential to mitigate GHG emissions. For example, Dilla et al. (2019) estimated C sequestration of 2.5 Mg C ha^{-1} in the Central Rift Valley of Ethiopia in above-ground biomass and 0.76 Mg C ha^{-1} in below-ground biomass. In addition, 118 Mg C ha^{-1} was stored in the 0–80 cm in soil depth under trees compared with 84 t C ha^{-1} in the soil of crop-only areas. In Mali, Takimoto et al. (2008) estimated C sequestration in above-ground at 54 Mg C ha^{-1} and 25 Mg C ha^{-1} in below-ground biomass. In addition, the estimated soil C sequestration was 70.8 Mg C ha^{-1} in the top 40 cm of the soil in parklands dominated by Faidherbia in the same area (Takimoto et al. 2008). SOC increases of 3–70% under Faidherbia canopy have also been reported in Sudan (Rhoades, 1995). At several sites in Malawi, SOC was 3–30% higher under Faidherbia canopy than in the open (Rhoades, 1995). In Tanzania, a 6-year-old stand of Faidherbia planted at a 5 × 5 m spacing accumulated 9.4 Mg ha^{-1} of wood C (Okorio and Maghembe, 1994). The carbon stored can play a critical role in mitigation of climate changes.

12.3.2.3 Economic Sustainability

In Eastern Ethiopia, Poschen (1986) compared the annual gross returns between a mixture of maize and sorghum grown in Faidherbia-based agroforestry with the same crops grown without the tree. In the Faidherbia system, three tree densities (6, 20 and 65 trees ha^{-1}) were compared. Local costs and prices were used as shadow prices or opportunity costs to express the value of physical units in monetary terms. Harvesting of wood was the only activity that involved substantial labour inputs. The calculations show that a single tree produces goods worth US$12 per year. Net incomes from Faidherbia-based agroforestry were highest at tree densities of 65 trees ha^{-1}. Gross returns from Faidherbia-based agroforestry were 8, 28 and 82% higher at tree densities of 6, 20 and 65 trees ha^{-1}, respectively, than in crops grown without the tree.

Similarly, Dewees (1995) estimated the costs and benefits of planting Faidherbia to improve crop yields in Malawi. The principal costs, which farmers bear, were for establishment and subsequent costs are minimal. The analysis assumed that a farmer would plant 100 seedlings, thinning out undesirable plants over the next several years, leaving a stand of 25 trees ha^{-1}. The analysis also assumed that yield benefits accrue slowly for the first 5 years, but more quickly in the 5–15th year and, then, slowly until the trees reach maturity by the 25th year. By the 25th year, yields of hybrid maize will be increased by 50% over the initial yields. Under these assumptions, the investment in Faidherbia makes good economic sense despite the long time before benefits accrue. For hybrid maize, the benefit-cost ratios remain >2 with proportional yield increase exceeding 30%, and establishment costs are kept below MK 100 (Dewees 1995).

12.3.2.4 Human Well-Being

Assessing food and nutrition security directly was a challenge due to the paucity of the requisite data, such as days additional food was available. However, from the crop yield data and other information in the literature, we could make some inferences. The increased availability of cereals, legumes and animal products produced in the agroforestry systems are expected to contribute to improved family nutrition.

Production risk, quantified as the probability of maize crops producing the target of less than 3 Mg ha^{-1}, was lower under the Faidherbia canopy than the open area. The probability of yields exceeding 3 Mg ha^{-1} was 0.5 under the canopy compared to 0.2 in the open area.

In the case study of Faidherbia-based agroforestry from Ethiopia (Hadgu et al. 2011), 97% of the respondents considered Faidherbia as beneficial tree species for improving their livelihoods by providing livestock fodder, bee forage, fuelwood and income through sale of wood products (e.g. mortars, wooden car stoppers, tables and stools). Respondents in eastern Ethiopia reported that they maintain Faidherbia trees on their farms for one or more benefits of maintaing Faidherbia on their farms: soil fertility improvement (84%), feed for livestock (59%) and income from sale of wood products (3%). In Northern Ethiopia, respondents mentioned that they gain benefits from Faidherbia including soil fertility improvement (95%), soil moisture retention (90%), rainwater infiltration (88%), bee forage (80%) and livestock feed (88%) as the main benefits. Similarly, in central Ethiopia, respondents mentioned soil fertility improvement (92%), livestock feed (84%), fuelwood (100%) and income from sale of products (81%). According to 37% of the respondents, higher crop yields are achieved with high Faidherbia tree densities.

12.4 Implications for Management

The influences of Faidherbia on soil and primary productivity are also size dependent; large trees will have larger areas of influence than small ones (Sileshi et al. 2014a; Sileshi 2016). Significant development in crown projection area starts when plants attain diameter at breast height of >40 cm, which was estimated to take about 22 years (Sileshi 2016). Once trees reach that size, the spatial extent of crown influence could exceed 100 m^2 tree^{-1}. With the average densities commonly reported in the literature (Table 12.1) and the mean annual diameter increment rates of 1.4–1.8 cm year^{-1} (Gebrekirstos et al. 2014; Sileshi et al. 2014a), the potential area of canopy influence was estimated to exceed 2000 m^2 ha^{-1} (Sileshi 2016) and canopy cover could reach 30%. At high densities (100–120 trees ha^{-1}), canopy cover could even reach 100% as is the case in the Matameye-Myrriah-Magaria area in Niger (Table 12.1).

Although the overall impact of Faidherbia is positive on crop productivity and soil health, the tree is highly variable in its growth (Sileshi et al. 2014a) and crown development with implications to its management in different regions. For example, Faidherbia develops greater crown radii on one side of the tree than the other side, depending on its location relative to the equator (Ismail 1986; Werger and Ellenbroek 1982). South of the Equator, Faidherbia tree crowns show a North/North-West orientation (Werger and Ellenbroek 1982), whereas in the North of the Equator, its crowns show a South/South-West orientation (Ismail 1986). If the trees were to be divided by a plane through the trunk in an East-West direction, crown biomass of the Southern and Northern half would have a ratio of 3:1 or 5:2 (Werger and Ellenbroek 1982) as shown in Fig. 12.1.

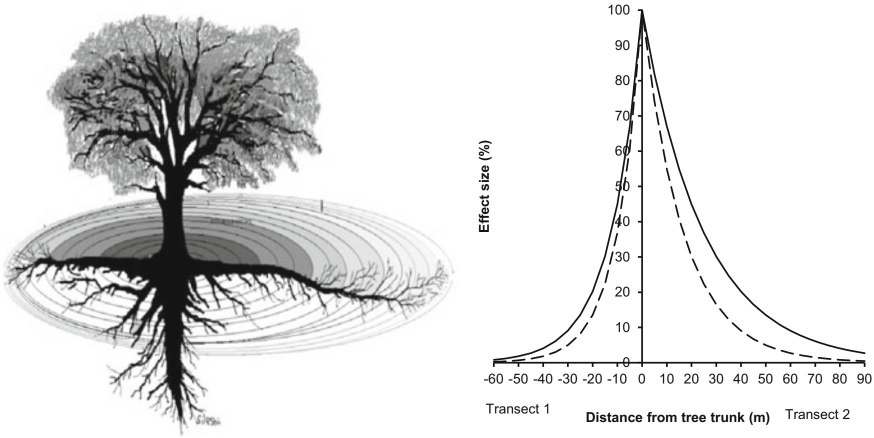

Fig. 12.1 Schematic representation of scenarios of variation in effects of tree canopy (*broken line*) and roots (*continuous line*) with distance from the tree trunk, depending on the geographic location of the tree (Northern or Southern Hemispheres)

The spatial extent of Faidherbia influence is usually far greater than that of the tree canopy projection, because the tree's influence through lateral roots often greatly exceeds the drip line (Fig. 12.1). For example, Faidherbia roots extend 2.5 times the crown radius in Zambezi riverine woodlands (Dunham 1991). This is, especially, the case in water-limited areas and shallow soils. The canopy influence can also be altered by farmers' management practices. For example, early lopping/pruning as is done in Ethiopia (Kamara and Haque 1992) may reduce crown cover to 38% of its original size (Louppe et al. 1996) and, thus, reduce the potential area of influence. Conversely, lopping/pruning may substantially shorten or cancel the reversed leaf phenology and stimulates refoliation during the rainy season. This may increase above- and below-ground competition with crops (Boffa, 1999). Intense pruning may also lead to a reduction in biomass production and consequently nutrient inputs to the soil (Louppe et al. 1996).

The growth and productivity of Faidherbia can also be influenced by density management. Sileshi et al. (2014a) demonstrated that Faidherbia conforms to the fundamental scaling rules underlying the growth-biomass-density relationship. While planting at high initial densities may result in slow growth, it may also produce higher biomass. In terms of biomass production, however, planting at 4 × 4 m spacing appears to be better than 6 × 6 m at least in the first 5–7 years (Lulandala 1989; Okorio and Maghembe 1994). For example, at 6 years after planting, Lulandala (1989) found higher wood yields (22 m^3 ha^{-1}) at 4 × 4 m compared with 10.3 m^3 ha^{-1} when planted at 6 × 6 m. Similarly, the total wood volume was twice as high (22.7 m^3 ha^{-1}) at 4 × 4 m spacing compared with 10.8 m^3 ha^{-1} at 6 × 6 m spacing (Okorio and Maghembe 1994). Foliage biomass was also twice as much (2.5 Mg ha^{-1}) at 4 × 4 m compared with 1.3 Mg ha^{-1} at 6 × 6 m spacing in 7-year-old plants (Okorio and Maghembe 1994).

Although high initial densities (e.g. 4 × 4 m spacing) may be beneficial for rapid site capture, competition may lead to poor growth and self-thinning. Conversely, low initial densities (e.g. 10 × 10 m spacing) could result in suboptimal use of site resources and failure to compensate for density-independent mortality (e.g. drought, fire, insects, diseases, etc.). Through modelling tree growth, Sileshi et al. (2014a) recommended a planting scheme involving 4 × 4 m initial spacing followed by progressive thinning to optimize site productivity.

12.5 Conclusions

The main conclusion from this review is that Faidherbia induces significant improvements in soil quality and productivity, especially, on inherently poor sites. In addition, Faidherbia does not mine nutrients from the surrounding open area; instead, it makes significant nutrient subsidies besides improving the growing conditions for crop. Therefore, the promotion of Faidherbia should be viewed as an important intervention towards increasing productivity and environmental sustainability, especially, in the nutrient-poor arid and semi-arid ecosystems. However, the sustainability of Faidherbia-based agroforestry parklands is threatened by poor regeneration and declining population of trees.

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Wood Anatomy and Response to Climate Variability of *Faidherbia albida* and *Prosopis africana* Using Dendrochronology in the Sahelian Agroforestry Parklands

13

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Abstract

Agroforestry parklands are the predominant agro-ecosystems in West Africa, where *Prosopis africana* and *Faidherbia albida* are among the key species. While these trees are resistant to external stress, their growth and regeneration depends strongly on local conditions. Meanwhile, the use of dendrochronology for characterizing tree growth and wood anatomy is limited in the Sahelian agroforestry parklands. This study was carried out in two agroforestry parklands in south-central Niger and aims at characterizing the wood anatomy and the response to climate variability of *P. africana* and *F. albida* trees using dendrochronological methods. Wood anatomy of these sections indicated that the density of vessels and rays were relatively higher in *P. africana* than in *F. albida*. The vessels in *P. africana* are arranged in radial clusters of up to four, whereas in *F. albida* they are solitary or in small groups of two. Both species form distinct growth boundaries. While growth boundaries in *F. albida* are characterized by alternating fiber and parenchyma bands and density differences between early and late wood, they are characterized by marginal parenchyma bands in *P. africana*. There was no significant difference in the mean ring width between the two-tree species ($p \leq 0.05$). However, annual radial growth varied from year to year in both species, indicating the strong influence of environmental

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factors. *P. africana* ($r1 = 0.63$) expressed stronger dependence on annual rainfall than *F. albida* ($r2 = 0.50$). On the other hand, *F. albida* is leafless during the rainy season, and hence strong correlations to annual rainfall is not expected. Nevertheless, the found positive correlation with annual rainfall indicates that the species is also dependent on rainfall amount, as groundwater recharge is higher during wet years. While we recommend further studies using older tree individuals, the low mean sensitivity (MS) value and high wood density of *P. africana* can be used as an indicator that it is less sensitive to drought. These results can guide practitioners and policy makers in the choice of species adapted to climate variability and other anthropogenic pressures in the Sahelian belt of Niger, and possibly in similar areas, while taking into account the needs of the local populations.

Keywords

Wood anatomy · Tree ring · Climate variability response · Dendrochronology · Sahel

13.1 Introduction

In the Sahel, trees play important socioeconomic and ecological roles (Larwanou et al. 2006; Liyama et al. 2014). Agroforestry systems make important contributions to enhancing food security and mitigating climate change by providing regulating, supporting, and provisioning services (Nair and Garrity 2012; Yélémou et al. 2013; Bayala et al. 2014). In West Africa, where climate change and variability are key priorities for rural development policies, several authors studied the potential of agroforestry systems and demonstrated their potential to sequester large quantities of carbon in all their compartments (Takimoto et al. 2008; Mbow et al. 2014; Bayala et al. 2014; Moussa et al. 2015). In many cases, these authors advocated in-depth assessments and regular monitoring of parkland tree species for improving local resilience of tree species and the people depending on them.

In order to better manage and ensure the sustainability of these agroforestry systems, especially agroforestry parklands, there is a need to improve knowledge of woody species and their ecological environments. Accurate information about the biomass productivity of these woody species would facilitate understanding of the growth and regeneration of these species and, more importantly, how they react to eco-climatic stresses such as recurrent droughts in the Sahel. Several methods to assess and monitor, including permanent plots placement or GIS and remote sensing, are used to study the dynamics of woody species (Mahamane et al. 2007; Mbow et al. 2013; Zhang et al. 2014). In recent studies, the accuracy of dendrochronology in determining the productivity of woody species was promising in sub-Saharan Africa (Mbow et al. 2013; Gebrekirstos et al. 2014a, b; Sanogo et al. 2016; Abiyu et al. 2018). Dendrochronology uses the information contained in tree rings to establish links with the rings' dynamics in time and space (Fritts 1976). In the boreal forests, for instance, dendrochronology has been used to reconstitute the past climate (Bégin et al. 2015), to build parameters of hydro-climatic regimes of rivers over time (Hughes 2002), or to reconstitute climatic information covering several centuries (Hughes 2002; Zhang et al. 2015).

Despite the challenges to the development of the methodology in the tropics, including false ring development and cross-dating problems (Tarhule and Hughes 2002; Worbes 2002; Gebrekirstos et al. 2014a, b), many authors have shown the great potential and applications of dendrochronology in several tropical species (Tarhule and Hughes 2002; Schöngart et al. 2006; Gebrekirstos et al. 2008; Krepkowski et al. 2013; Mbow et al. 2013; Boakye et al. 2016; Mokria et al. 2017; Gaspard et al. 2018; Granato-Souza et al. 2018). In West Africa, Tarhule and Hughes (2002) classified various species into potentially problematic and unsuitable species due to their wood anatomy, in particular the distinctiveness of their ring formations and the possibility of cross-dating. Studies on the species Vachelia (Acacia) spp. showed variability in the growth and responses of these species to climatic conditions in sub-Saharan Africa (Gourlay 1995; Nicolini et al. 2010).

The characterization of the growth dynamics of woody species in the Sahel has an important implication for understanding the dynamics of ecosystems and their ability to respond to climate variability (Nicolini et al. 2010). A good adaptation to climatic variability would be a strong signal for choosing species that can be selected by policy makers for climate change mitigation in these ecosystems. *Faidherbia albida* and *Prosopis africana* are two species of socioeconomic and agronomic importance and are widely distributed over south-central Niger (Kho et al. 2001; Garrity et al. 2010; Weber et al. 2015; Laouali et al. 2016). These two species are well established in the production systems of many rural populations in Africa. Very few studies (Gebrekirstos et al. 2014a, b) have addressed the anatomical and growth characteristics of these two species in the Sahel in general and in Niger in particular. Therefore, the objective of this study is to characterize the anatomy and responses of these two species to climatic variability, using dendrochronological methodology, in the agroforestry parklands in the Sahelian zone of Niger. This will guide practitioners and policy makers to choose the species best adapted to the Sahelian environment in the context of future climate changes.

13.2 Study Area, Wood Sample Collection, Wood Anatomy, and Data Analysis

13.2.1 Study Sites

The parklands of *P. africana* and *F. albida* are respectively located at 13°25'N, 006°58′E (site 1, south Maradi) and 13°54′N, 007°18′E (site 2, northeast Maradi) in Niger (Fig. 13.1). The soils are dominantly ferruginous and slightly leached and clayey in the two sites. Site 1 is characterized by a Sudano-Sahelian climate, whereas the climate in site 2 is purely Sahelian. The average rainfall (1950–2014) was 526.39 ± 127.89 mm. The long-term (1970–2013) average maximum and minimum

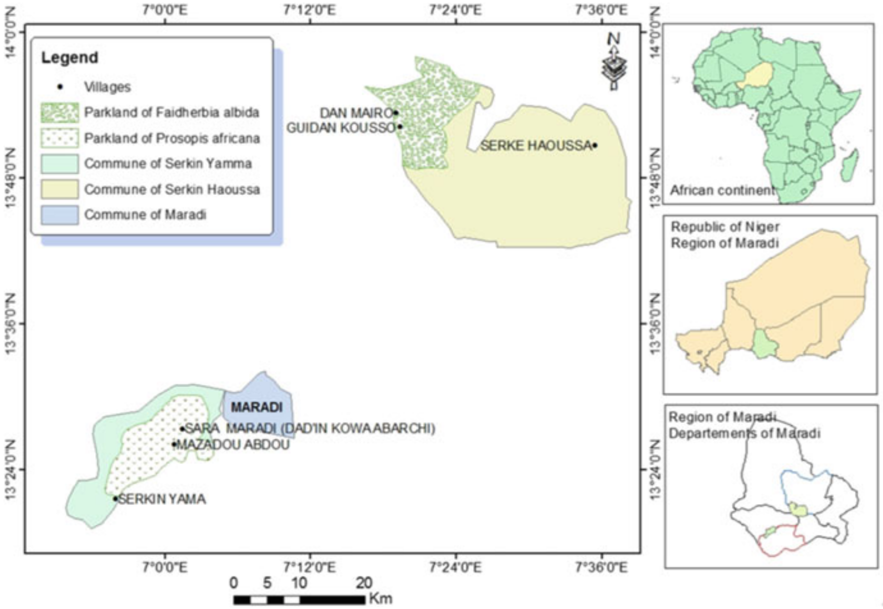

Fig. 13.1 Location of study sites

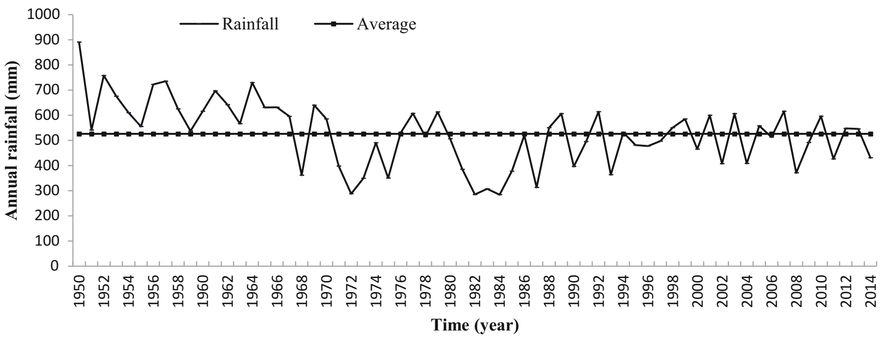

Fig. 13.2 Interannual variability of rainfall in the area study

temperatures were 35.0 ± 0.7 °C and 20.8 ± 0.6 °C, respectively. There are three main seasons: the cold dry season from November to March, the warm dry season from March to June, and the wet season from July to October.

The rainfall has drastically decreased over the recent years relative to the period 1950–1970 (Fig. 13.2). There are three moist months in the study area: July, August, and September (Fig. 13.3). Water is available at the root zone ($P \geq 1/2 \times$ ETP; P = rainfall and ETP = evapotranspiration) only during these 3 months (Boudet 1984; Fig.13.4). The other months are considered dry. Therefore, the study area experiences a very long dry season with a very short rainy season characterized by important intra-seasonal rainfall variability.

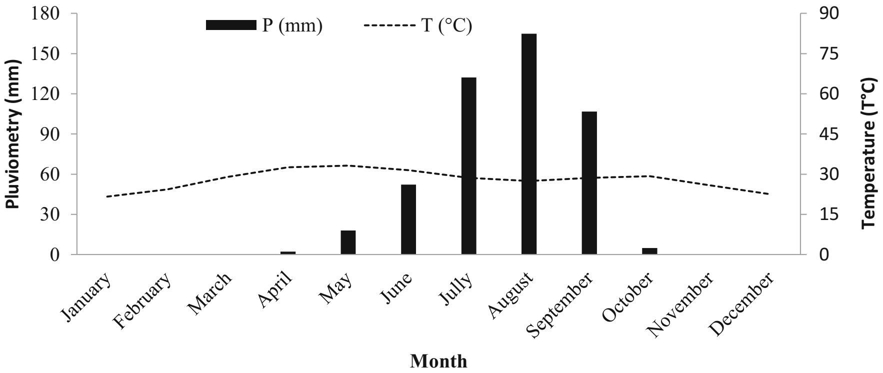

Fig. 13.3 Climatic diagram of the area study

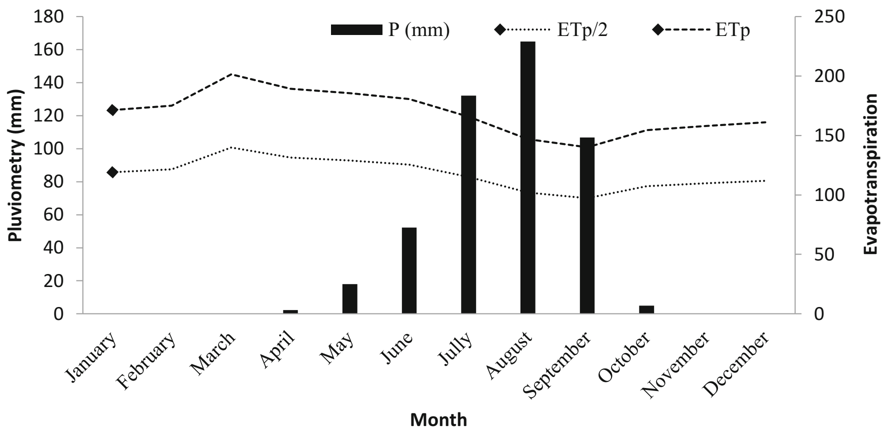

Fig. 13.4 Water balance diagram of the study area

13.2.2 Sample Collection

Stem discs of ten trees of each species at each site were selected for analysis, making a total of 40 trees harvested. The trees were cut down in February–March of 2015, and 5-cm-thick samples were taken from the trunks at 1.30 m above ground level in order to reduce the influence of external factors by considering the basal diameter (Lébourgeois 2010). Each stem disc was marked according to the species, site, and tree number and oven-dried at 100°C for one week.

13.2.3 Wood micro-sections preparation

For the anatomical analysis of the woods, a cross-section of the discs was used. At each site, one disc of each species was considered. Wood pieces 2 cm wide were taken from the pith to the bark. Each piece was divided into two parts, from heartwood to sapwood, in order to facilitate cutting high-quality microsection with the sliding microtome. The samples were soaked in a mixture of water (50%) and glycerol (50%) for several days to increase cambium cell stability and make the wood softer. Due to *P. africana* wood being very hard, it was put in boiled water for several hours in order to accelerate its tenderness.

Thin cuts of 20–30 μm thickness were made to remove the superficial stratum of the cross-section using the microtome. In order to make the cuttings more tender and thin, a solution made of 10 g of cereal flour (corn), 8 ml of glycerol, and 7 g of water was regularly applied to their cross-sections (Montwé et al. 2015). The microsections were placed on slides and dried for one day. The slides were subsequently sprayed with astra-blue and safranin solutions to color the wood components and dehydrate the sections with water, ethanol at 50% and 96%, and di-methoxy-propane at 10% (Gärtner et al. 2015). Thereafter, solutions of rohistol xylene and balsam of Canada were applied to the slides (Gärtner et al. 2015) and covered with lamellae. This allows for distinguishing clearly the different elements of the cross-section of the wood, in particular the vessels and fibers. Well prepared, the slides were photographed using the Olympus BX 43 microscope system, and the images were properly adjusted according to the color intensity.

13.2.4 Development of Chronology Series

13.2.4.1 Measurements of Ring Width

The analysis was carried out using standard techniques in dendrochronology (Pilcher 1990). After drying, the discs were gradually smoothed with sandpaper (80–800) until the individual rings were clearly visible. For each disc, two radiuses of different direction from pith to wood bark were drawn to identify false and missing rings. Depending on each radius, the boundary of each ring was identified, marked, and followed until its accuracy was confirmed by means of a stereo-microscope (Leica) with a magnification of 0.63. The width of the rings was measured, from pith to bark, in micrometer (1/1000 mm) using the LINTAB 6 system equipped with the TSAP-Win software, which is a powerful software for measuring, analyzing, and presenting the ring width (Rinn Tech 2010).

13.2.4.2 Cross Dating

The cross-dating was done at two levels, one between the two radii of each tree and another between the trees of the same species using TSAP-Win software. Two approaches were combined: statistical (mathematical) and graphical synchronization (Rinn 2010). For the first, the main criteria considered for growth similarity were: GLK “Gleichlaüfigkeitskoeffizient,” or sum of the equal intervals of slope, expressing the year-to-year harmony percentage of fluctuation of two series in a period of overlap (Schweingruber 1988), and TVH or Hollstein t-value (1980), expressing the degree of similarity of two curves (Baillie and Pilcher 1973). The graphic method allowed for superimposing the measurement curves of each radius in order to identify, facilitate, and find the highest tree growth similarity (Copper 1979).

When cross-dating was successful, the mean ring width series for each tree were calculated in order to establish a second cross-dating much more rigorous and more precise by means of the COFECHA program. This is a software program that evaluates the quality of cross-dating and the precision of ring width measurements (Grissino-Mayer 2001). For each of the two study species, the ring width averages of the series were cross-dated at a 1% confidence level. A higher growth similarity between trees was found when the critical correlation of series was less than the inter-series correlation (Grissino-Mayer 2001). At the end of the cross-dating procedure, only those trees that passed the COFECHA test were retained. Based on this, the cross-dating application retained 11 discs of trees and eliminated nine others for each species. The 18 discs were discarded because their growth was peculiar compared to the predominantly observed common growth pattern of trees, or because they were damaged due to anthropogenic pressure (destroyed pith), or by the inability to identify wedged rings. In addition, two discs were very small in size to the point that they did not meet the minimum age required (5 years) to be processed with the TSAP-Win software. It should be noted that the annual growth of trees may be the result of several factors, including climatic and non-climatic factors (Cook 1985). Using the ARSTAN program, the individual series were standardized by eliminating "noises" or non-climatic disturbances and estimating annual ring width averages for each series (Cook and Holmes 1985). The "noise" values were called residues. Thus, the standardized chronology was elaborated for each tree.

13.2.5 Data Analysis

Annual rings were processed with the TSAP-Win, COFECHA, and ARSTAN programs to determine statistical parameters including mean width, standard deviation, mean sensitivity (MS), and autocorrelation (AC) (Douglass 1937). The average ring width of each tree was calculated at two levels, both on the basis of individual chronologies and on that of the stand.

Mean sensitivity (MS) was calculated using the following formula (Schweingruber 1988):

$$\mathrm{MS}_j = \frac{1}{n-1} \times \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{(x_{t+1} + x_t)} \right|. \tag{13.11}$$

For the population, MS was calculated using the following formula:

$$\mathrm{MS}_i = \frac{1}{n-1} \times \sum_{t=1}^{t=n-1} S_j, \tag{13.22}$$

where n = number of years, x_t = ring formed in year t, and x_{t+1} = rings formed in year t + 1.The mean sensitivity varies from 0 to 2. It is equal to 0 when the widths of two successive rings are equal and to 2 when one of two successive rings is 0. Finally, the variance analysis test (ANOVA) was applied to compare the average of ring widths between the two species.

Finally, the standardized master chronology was used to relate the annual growth fluctuations in the two species. The Pearson correlation test was applied at 5% threshold to determine the degree of dependence of each species on annual rainfall.

13.3 Key Observations and Inferences

13.3.1 Wood Anatomy Characteristics

The cross-section of the wood allowed us distinguishing arrangement of long dense filaments of rays between which vessels of varying size were arranged in *P. africana* and *F. albida* (Fig. 13.5a_1 and a_2).

The heartwood rays were more pronounced in *P. africana* than in *F. albida*. The appearance of the wood was brighter in sapwood than in heartwoods for both species. Between two neighboring rings, light bands indicated earlywood and dark bands indicated latewood (Fig. 13.5b_1). The vessels in *P. africana* are arranged in radial clusters of up to four (Fig. 13.5a_2), whereas in *F. albida* they are solitary or in small groups of two (Fig. 13.5a_1). The vessels in *P. africana* are surrounded by clusters of paratracheal parenchymatic cells, whereas in *F. albida* they are embedded in tangential parenchymatic bands. Both species form distinct growth boundaries. Growth boundaries of *F. albida* are characterized by alternating fiber and parenchyma bands and density differences between early and late wood (Gebrekirstos et al. 2014a, b), while *P. africana* is characterized by marginal parenchyma bands.

13.3.2 Ring width characteristics

Cross dating was successfully performed for 11 of the 20 trees of each of the two species. The other discs were not used for further analysis because they were not cross-dated successfully. Of the 11 trees, six were from the Sarkin Yamma site and five from Dan Mairo for *F. albida*. The same observation was made for *P. africana*. The chronology age ranged from 7 to 25 years for *P. africana* and from 7 to 33 years for *F. albida* (Table 13.1). The diameter at breast height (DBH) varied from 6.1 to 33.1 cm and from 5.7 to 47.8 cm, respectively, for *P. africana* and *F. albida*. The annual cambial growth of rings ranged from 0.53 ± 0.16 to 1.58 ± 0.29 mm for *P. africana* and from 0.37 ± 0.14 to 2.14 ± 0.69 mm for *F. albida*. There was no significant difference ($F = 0.04$; $P = 0.84$) in annual growth of cambium between the two species.

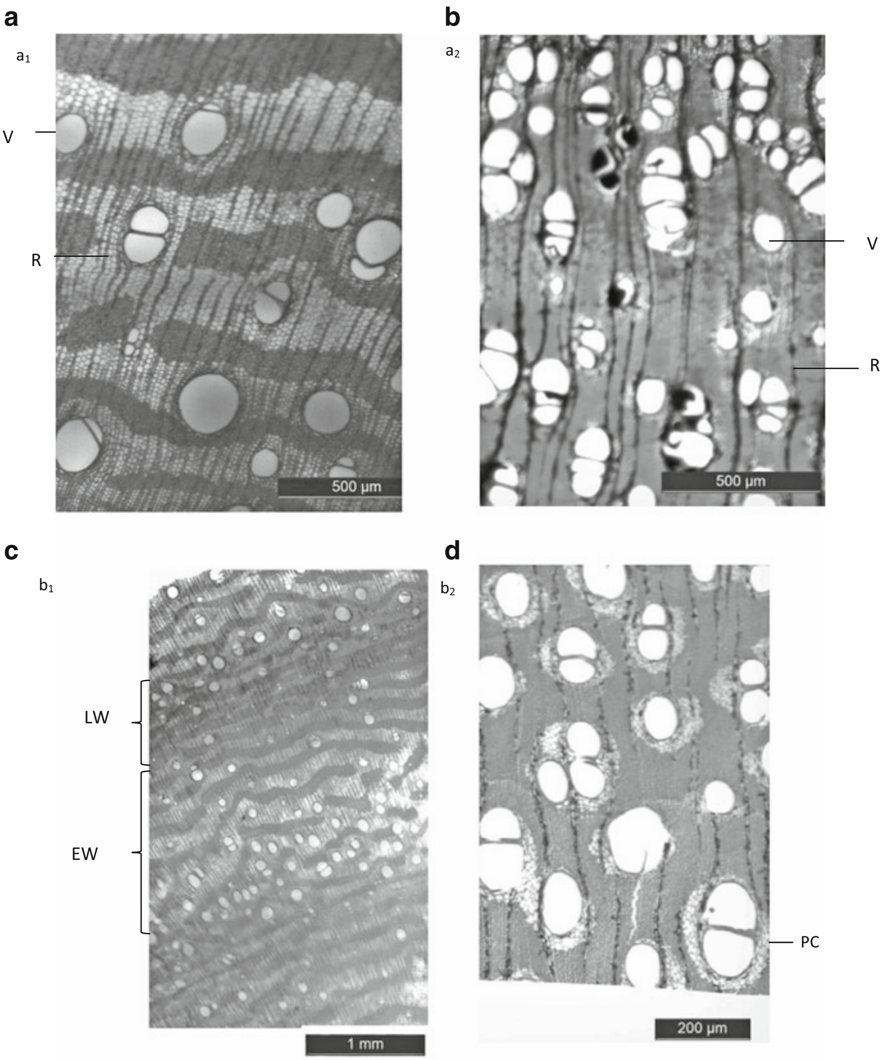

Fig. 13.5 Anatomy of *Faidherbia albida* ($\mathbf{a_1}$, $\mathbf{b_1}$) and *Prosopis africana* ($\mathbf{a_2}$, $\mathbf{b_2}$) from heartwood (**a**) and sapwood (**b**). *V* vessels; *R* rays; *LW* latewood; *EW* earlywood; PC parenchyma cells

13.3.3 Ring Width and Response to Climate Variability

The mean sensitivity (MS) and autocorrelation (AC) were, respectively, 0.35 and 0.37 for *P. africana* and 0.435 and 0.452 for *F. albida* (Table 13.2). The residue values were 1.07 ± 0.19 mm in *P. africana* and 1.04 ± 0.36 mm in *F. albida* (Table 13.2).

Table 13.1 Characteristics of the master chronology

Species	*N*	Age (year)	DBH (cm)	Annual cambial growth (mm)		
				Mean	Minimum	Maximum
P. africana	11	7–25 (1991–2015)	6.05–33.12	1.004 ± 0.23a	0.53 ± 0.16a	1.58 ± 0.29b
F. albida	11	7–33 (1983–2015)	5.73–47.77	1.06 ± 0.42a	0.37 ± 0.14b	2.14 ± 0.69a

In the same column, values with the same letter are not statistically different ($p > 0.05$). Those with different letters are statistically different ($p < 0.05$)
N number of trees; *DBH* diameter at breast height (or 1.30 m from the ground)

Table 13.2 Variation in the mean sensitivity (MS) and autocorrelation (AC) residues and correlation of the master chronology according to the species

Species	MS	AC	Residues (mm)	Inter-series correlation	Critical correlation	GLK (%) ± σ	TVH ± σ
P. africana	0.35 ± 0.09	0.373	1.07 ± 0.19	0.418	0.4093	82.77 ± 12.07	5.34 ± 4.78
F. albida	0.43 ± 0.07	0.452	1.04 ± 0.36	0.446	0.4093	80.09 ± 9.02	5.27 ± 3.20

MS mean sensitivity; *AC* autocorrelation; *GLK* harmony percentage from year to year of fluctuation for two series; *TVH* Hollstein *t*-value

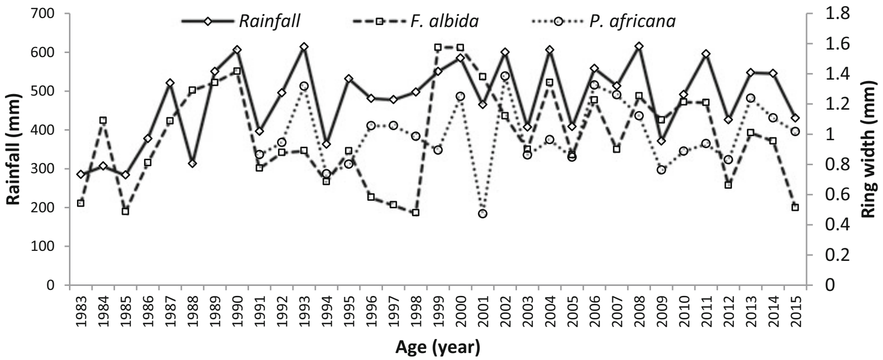

Fig. 13.6 Relationship between master chronology and the annual precipitation for the two species

Ring widths fluctuated from 1 year to another. The ring width growth was slightly lower from 1983 to 1986. A marked increase in ring width growth was observed in 1986 for *F. albida* and thereafter decreased. There was no clear trend in ring width growth among the two trees species. However, from 1991 to 1998, the ring width values were markedly increased in *P. africana* trees. During the period from 1999 to 2002, ring growth was higher in *F. albida*. From 2008 to 2014, ring growth fluctuated and showed no clear trend for either species (Fig. 13.6). This annual ring growth fluctuation correlates with the average annual rainfall. The Pearson correlation was $r_1 = 0.50$ for *F. albida* and $r_2 = 0.63$ for *P. africana*.

13.4 Discussion

The configuration of the anatomical elements (vessels, rays thickness) differed between the two species in the current study. This difference could be related to the intrinsic nature of the two species. The anatomical elements including arrangement, grouping, abundance, and sizes of vessels remain important for wood identification (Regent Inst 2012). Similar observations were made in West and Southern African woody species by Tarhule and Hughes (2002), Gebrekirstos et al. (2008), and Mbow et al. (2013). The cuts made on *P. africana* for anatomical observation appeared to be difficult, which led to boiling the wood in order to make it more tender. The difference in the ease of cuts between the two tree species could be related to wood density. *P. africana* wood, at 0.72 ± 0.06 g cm^{-3}, is relatively heavy compared to *F. albida* at 0.51 ± 0.02 g cm^{-3} (Moussa and Larwanou 2018). These results are partly in agreement with those of Tarhule and Hughes (2002), who classified *P. africana* as a species with problematic potential in dendrochronology. These authors used as criteria distinctiveness of ring boundaries, ability to achieve cross-dating between radii, circuit uniformity, ring wedging, and variability of ring widths. The problematic category includes samples for which a combination of desirable characteristics is observed, but these require greater diligence to detect and imply a higher probability of error (Tarhule and Hughes 2002).

In the tropics, the annual growth of cambium is marked by ring formation. In the Sahel, due to the unimodal character of rainfall, a full ring constitutes an annual growth of cambium (Nicolini et al. 2010; Sanogo et al. 2016). The positive correlations found between the chronologies and annual rainfall may also substantiate the annual nature of the growth rings (Gebrekirstos et al. 2008). Worbes (2002) explained that the problem of false ring formation could be related to many factors; including competition for growth factors (e.g., light) and bush fires that limit the productivity of the tree. At both sites, the density was low to induce competition, and no bush fire was observed. In dryland areas of sub-Saharan Africa, the problem of cross-dating for woody species is widely shared by many studies (Gebrekirstos et al. 2008; Nicolini et al. 2010; Mbow et al. 2013). Thus, the problems associated with ring identification have become one of the fundamental limits of the application of dendrochronology in the tropics (Worbes 2002; Gebrekirstos et al. 2014a, b).

The ring width growth was highly oscillating, with a significant difference in extreme values for both species. The means of ring width values were 1.004 $\pm$ 0.23 mm in *P. africana* and 1.06 $\pm$ 0.42 mm in *F. albida*. These values are comparable to the average width (1.001 mm and 1.005 mm) values reported by Nicolini et al. (2010) for *A. seyal* in the Sahelian part of Niger. In Ethiopia, Gebrekirstos et al. (2008) reported tree ring widths ranging from 1.81 $\pm$ 0.46 mm for *A. tortilis* to 2.53 $\pm$ 0.35 mm for *A. senegal*. In Benin and Ivory Coast, Schöngart et al. (2006) found annual ring width growth of 1.07 $\pm$ 0.29 mm in *Diospyros abyssinica* tree plantations and 3.10 $\pm$ 1.74 mm in *P. erinaceus* plantations. Using several Vachelia species, Gourlay (1995) found a radial variation in non-standardized data ranging from 6 to 7 mm in Kenya. It is worth noting that these studies were not conducted in the same climatic conditions, and therefore, the outcome could change from one area to another. The differences in ring widths observed in the current study from those reported from the studies cited above may be explained by the fact that the rainfall of the present study area was around 500 mm per year, which was considerably lower than that of the areas of the above studies, where the annual rainfall was generally greater than 800 mm. Another possible explanation for this is that species phenology could be also a factor. *P. africana* and *F. albida* are two non-evergreen species in the Sahel. *P. africana* is a deciduous long-leaved species, while *F. albida* is deciduous in the off-season (Wood 1992; Roupsard et al. 1999; Gassama-Dia et al. 2003). It also seems possible that the management practices are a factor. In fact, with the installation of the crops, the trees were cleared through the practice of farmer-managed natural regeneration (Larwanou and Saâdou 2011), and large branches were pruned to reduce competition for light with crops, especially for the specific case of *P. africana*, which did not lose its leaves during the rainy season. The branches of *F. albida* undergo cuts for foliage that was used for livestock feed during the dry season. In fact, this partly explains the problems with cross-dating of some of the stem discs observed in this study and were in accordance with those found by Gebrekirstos et al. (2008) in anthropogenic pressure fields in Ethiopia. *F. albida* showed greater growth fluctuations than *P.*

africana. This observation was corroborated by the values of mean sensitivity and autocorrelation. In general, for both species, SM and AC were high, explaining a strong influence of environmental factors on their growth. This was mainly confirmed by residue values (Table 13.2). These results were similar to those found by Nicolini et al. (2010) in Niger on *P. africana* with MS between 0.32 and 0.35, AC between 0.50 and 0.54, and residue close to 1 mm.

The correlation between annual ring width and precipitation was higher in *P. africana* than in *F. albida* trees. This indicates that the former species depends more on rainwater compared to the latter one in the area. This difference may be due to the fact that *F. albida* sheds its leaves during the rainy season and develops a deeper root system that can reach underground water to compensate for the annual water deficit (Vandeubeldt 1991; Alexandre and Ouedraogo 1992). On the other hand, the correlation of temperature with the annual growth of rings was very insignificant with these two species, and it is in accordance with other studies from Ethiopia (Gebrekirstos et al. 2008). The annual growth of *F. albida* is different from that found by Gebrekirstos et al. (2014a, b). Indeed, they found an average annual growth of 9.34 mm in the agroforestry parklands of Malawi. This difference in growth from the results of this study could be explained at first by the annual rainfall. In Malawi, the annual rainfall of sites was between 1100 and 1300 mm, while for this study it was around 500 mm. Moreover, the data of Gebrekirstos et al. (2014a, b) have not been standardized to extract non-climatic signals. In addition to rainfall, morphological variations of *F. albida* have been reported (Fagg 1992). Ibrahim et al. (1997) highlight three different ecotypes of *F. albida* in Africa. These were the Sahelian ecotype, the South African ecotype, and the ecotype that overlaps the two zones, particularly in Ethiopia. In the same ecological zone, *F. albida* has contrasting morphological and growth variability (Chevalier et al. 1992; Billand 1992; Roupsard and Dreyer 1998). Provenances from southern Africa are more efficient in growth than provenances from West Africa (Dangasuk et al. 1997). The study of the genetic variability of West, Central, and East African provenances has shown a large complementary difference between the generic heritages of these areas (Joly 1992).

The master chronologies for the two species were obtained using rings after eliminating non-climatic signals. The relatively slow growth of rings observed during 1983–1986, 1994–1999, and 2004–2006 could be explained by drought occurrences observed in the Sahel during those periods. This reflects the relative dependence of these species on the precipitation in the area and confirms the hypothesis that tree growth in the tropics is rain-dependent (Worbes 2002; Gebrekirstos et al. 2014a, b).

13.5 Conclusion

This study revealed the differences in wood anatomy and ring widths of *P. africana* and *F. albida* in the agroforestry parklands in the dryland of Niger. The environmental conditions, including rainfall, exert a major influence on the diameter growth of these two species. This study revealed a reduction in ring widths during periods of drought and water deficit encountered in Niger for several years. *P. africana* was more dependent on rainfall than *F. albida*. There is, however, a need to confirm these results with long chronologies in order to better understand the growth dynamics of these two species as well as their capacity to respond to the climatic variability of the zone. It will also be important to analyze annual growth rings by micro-densitometry in order to provide information ranging from cambial growth modalities to the anatomical properties of the wood of both species. They will make it possible to specifically link the variations of the density at the ring scale to the cambial operation through the variations of the rainfall at the scale of the sites (studies of the climatic data). This would help in developing the most appropriate management and reforestation strategies for mitigating climate change effects in the Sahe.

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Lac-Based Agroforestry System for Degraded Lands in India

14

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Abstract

Agroforestry systems are being increasingly adopted for diversification and sustainability of production on degraded lands for increased social, economic and environmental benefits. Although the practice of nurturing trees on farm and other lands is quite old, the renewed emphasis on scientific management for optimum productivity and economic gains is recent.

The lac, a natural heritage of India, has long been associated with tribal and poor people for regular income when it is not possible to grow other cash crops. The lac-based agroforestry has an important dimension as the lac growers protect host trees in wasteland and community lands and thus, contribute in arresting the trend of forest degradation. Opportunities for farm and tribal communities exist for transforming the traditional lac-based agroforestry into modern remunerative venture from degraded lands. Multi-tier models such as *Schleichera oleosa* + *Ziziphus mauritiana* + *Flemingia semialata* + vegetable have been found successful for the tribal belt of central plateau region of India. The model provides additional income and nutritional supplements from fruits and vegetables and may also act as a buffer in case of failure of the main product (lac) on account of some unpredictable and uncontrolled factors in a given season.

In view of bright prospects of international lac markets and feasibility of lac cultivation on degraded lands in many states of India, viz. Jharkhand, Chhattisgarh, Madhya Pradesh, West Bengal, Maharashtra, etc., promotion of improved technologies in context of lac-based agroforestry may be of immense value in India in the coming years. This chapter describes such technologies.

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The insect taxonomy · Traditional agroforestry systems · Developed agroforestry systems

14.1 Introduction

Agroforestry practice encompasses a wide range of trees grown on farms and other lands for creating enterprise as well as livelihood opportunities (Roshetko et al. 2007). In many developing countries, including India, land degradation and desertification need urgent attention for sustainable livelihood for the farming community. Since land resources are finite, requisite measures are required to reclaim degraded and wastelands. In India, a substantial area falls under the category of wasteland or degraded land. The area under forests is shrinking due to demographic pressures. In such a scenario ample opportunities exist for promotion of region-specific agroforestry interventions on farmlands and degraded lands for enhancement in farmers' income vis-à-vis soil and water conservation, etc.

Lac is a natural heritage of India, mentioned in the 3000-year-old Mahabharata epic. It was known to Romans and was introduced to Europe at the end of the sixteenth century. The lac-based farming is associated with tribal and poor people in providing steady income in the absence of other cash crops. It provides an effective option to utilize degraded lands without any ecological disturbance. Over three million tribals of Jharkhand, Chhattisgarh, Madhya Pradesh, West Bengal, Odisha, Gujarat, Maharashtra, Uttar Pradesh, Andhra Pradesh and Assam states of India are engaged in lac production. It is traditionally cultivated in forest trees such as *Butea monosperma*, *Dalbergia sissoo* and *Ficus*, known to contribute in the maintenance of soil fertility. Besides, these species are reported to preserve fragile ecosystem (Saint-Pierre and Bingrong 1993; Orwa et al. 2009).

The remotely located tribal villages mainly survive on sustenance farming, and the lac cultivation generates a substantial monetary income. Lac contributes around 20–38% of the total agricultural income of the tribal growers of Jharkhand (Jaiswal et al. 2006; Shah et al. 2015). Nearly one million man-days per annum are generated by the lac processing industries. Besides providing high return to the lac farmers, it has certain other merits which made this commodity as a sustainable and eco-friendly intervention in the agroforestry sector. Apart from the lac production and increased soil fertility aspects, the lac hosts also play an important role as arthropod bank that protects crop from many pests (Sharma et al. 2006; Youqing et al. 2010).

Lac is a natural resin, biodegradable and non-toxic; it commands high demand in food, textiles, paints and pharmaceutical industries (Sharma et al. 2006). Looking to the prospects in international market, it is presumed that in the coming years lac cultivation will be more and more profitable (Patil et al. 2013). Globally, lac is produced in India, Bangladesh, China, Laos, Mexico, Myanmar, Thailand and Vietnam. India is the largest producer, accounting for about 50–60% of the total world lac production. The production in 2014–2015 was in the tune of 17 thousand tons (Yogi et al. 2017). About 60 countries mainly Bangladesh, Egypt, Germany, Indonesia, Italy, Nepal, Pakistan, Spain, UAE and the USA are importing lac products from India. India earns about INR 1200–1300 million (US$17–19 million) of foreign exchange annually by exporting lac.

Incorporation of improved cultivation techniques in the traditional lac-based agroforestry systems has the potential to enhance income generation of the tribal/ farming community in the central plateau region of India. Cultivation of lac, and rearing of its insect, requires technical skills; hence, a general information of lac insect, cultivation technique and economic benefits are specifically discussed in Sect. 14.2 of the chapter. In the subsequent sections, traditional farming system, improvisations done in the traditional practices and the improved agroforestry systems are presented.

14.2 Lac Cultivation

Lac is a crimson-red resin secreted by lac insects. Thousands of lac insects colonize the branches of the host trees and secrete the resinous pigment. For cultivation the farmer ties a broodlac (a stick that contains eggs ready to hatch) to the tree to be infested. The lac-encrusted branches of the host trees are cut and harvested as sticklac (Derry 2012). The sticklac after washing and removing impurities is termed as seedlac. This seedlac contains around 3–5% impurities and is further processed into shellac and other by-products by heat treatment or solvent extraction (https://en.wikipedia.org/wiki/Lac). Management of lac insects to obtain a high amount of quality lac includes selection and maintenance of host plants, inoculation of host plants with healthy broodlac and protection against pests and diseases.

14.2.1 The Insect

Taxonomy

The lac insect belongs to order Hemiptera, superfamily Coccoidea and family Tachardiidae. In India, two genera, namely, *Kerria* and *Paratachardina*, are found. The insects belonging to genus *Paratachardina* have a single generation in a year, termed as univoltine, while *Kerria lacca* (Kerr) have two generations in a year, termed as bivoltine, and some even have three generations (*Kerria sharda*) termed as trivoltine. There are two strains (biotype) of *Kerria lacca*, namely, *rangeeni* and *kusmi*. Each of these strains completes its life cycle twice in a year, thus, producing two crops in a year.

Life Cycle

Lac insect is a minute, soft-bodied, crawling scale insect, which inserts its mouth (proboscis) into plant tissue, sucks juices, grows and secretes resinous lac from the body and finally gets covered in it. Lac is secreted by insects for protection from

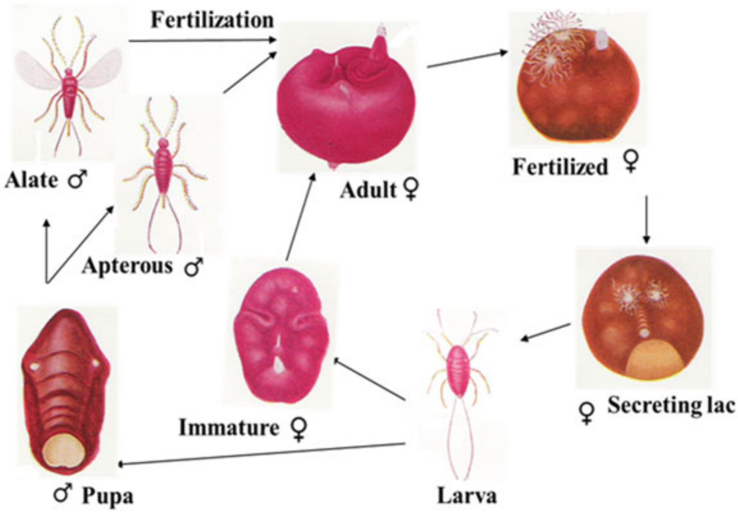

Fig. 14.1 Lac insect and its life cycle

predators. Male and female differ in form and developmental stages. Male is red-coloured, winged insect and 1.2–1.5 mm in length. It has reduced eyes and antennae. Female is larger than male, measures 4–5 mm in length and has a pyriform body (head, thorax and abdomen are not clearly distinct); wings are absent, and antennae and legs are degenerated (Fig.14.1).

The life cycle of insect takes about 6 months. The embryonic development of lac insect takes place in the body of the adult female (ovoviviparity), and the hatching of eggs takes place in the specially built incubation chamber. The life cycle of lac insect starts with its first-instar larval stage, the crawlers. The first-instar larvae emerged from mature female cell, moulting to the second instar. The male and female lac insects can be distinguished at the second instar. The second instar of male is elongated cigar shaped, while female is round in shape. The second-instar male insect transforms into pupa (pseudopupa). The pupa remains inside the outer covering of the second instar, which does not shed. The adult male insects emerge out of pupa by removing its operculum. Sexually mature male and female insects mate. The crawling adult of male reaches the sedentary female adult. It has been found that one male insect is capable of mating 40–45 females and vice versa (multiple coitus). The life span of adult male insect is only 1–3 days after its emergence from pupa. They die after mating, while female insects survive up to crop maturity stage.

After fertilization, the female insect oviposits inside the cell secreted by it. A mature female insect oviposits on an average of 300–400 eggs. During egg laying, it contracts its body, thus creating a space between the body and resin wall. The eggs are laid in this space and hatch immediately after laying. The larvae remain inside the resinous cell until the environmental conditions outside become suitable for them. Thousands of first-instar larvae crawl out from the cell, termed as swarming.

Normally larval emergence takes place from 8:00 a.m. to 12.00 noon. The emergence slows down after 2.00 pm and virtually ceases after sunset. Larval emergence continues for about a fortnight but may vary according to season and temperature.

14.3 Host Plants

Lac host trees can be divided into three categories, depending on the insect strains: (1) tree species on which only *kusmi* lac farming can be done, such as *Schleichera oleosa* (kusum); (2) trees on which *rangeeni* lac farming can be done, such as *Butea monosperma* (palas); and (3) trees on which both *rangeeni* and *kusmi* lac farming can be done, e.g. *Ziziphus mauritiana* (ber)*, Acacia catechu* (khair), *Albizia lucida* (Galwang), *Calliandra calothyrsus* and *A. auriculiformis* (akashmoni). Besides, *Ficus glomerata* (dumber), *F. infectoria* (pakur), *F. glabella* (putkal), *F. cunea* (porho), *F. religiosa* (pipal), *Ougeinia oojeinense* (sandan), *Albizia lebbeck*, *Croton oblongifolius* (putri) and *Dalbergia latifolia* (sissoo) are other potential lac insect host trees on which lac farming is done by the farmers (Jaiswal et al. 2001; Jaiswal 2012; Vaibhav et al. 2016).

14.3.1 Management of Host Plant

Management of lac crop is an essential activity for the growth and development of lac insect (Fig. 14.2). The pruning of trees is an essential to have sufficient number of tender, succulent and healthy shoots for inoculation, feeding and establishment of newly emerged immature stages of lac insect. Pruning is generally scheduled for April. After pruning new shoots emerge during October–November. At this time inoculation of host trees is done by tagging broodlac (a lac stick with mature gravid living mother cell) on new shoots. The young larvae come out and settle on shoots of host plant. After complete emergence of larva from broodlac, the used up bundles (*phunki* bundles) are to be removed from the tree. This is an essential operation in order to minimize the attack of predators and parasitoids to the new lac crop and is also necessary to avoid wastage of lac as these *phunki* sticks are also marketable (Table 14.1) (Jaiswal et al. 2011; Ghosal et al. 2018). Regular monitoring for pest and disease attack is essential depending on the crop season, type and location of host tree/plant and environmental conditions. The lac is harvested as either a mature or immature lac from tree along with host twigs. The maturity is assessed by post-embryonic developmental stages of lac larvae inside the mother cell. The harvested lac is scraped, sold in market or kept for air-drying.

14.3.2 Commercial Products

Lac insect secretes three natural products of commercial importance, i.e. resin (lac), wax and dye. The commercial forms of the lac resin are seedlac, shellac, bleached lac

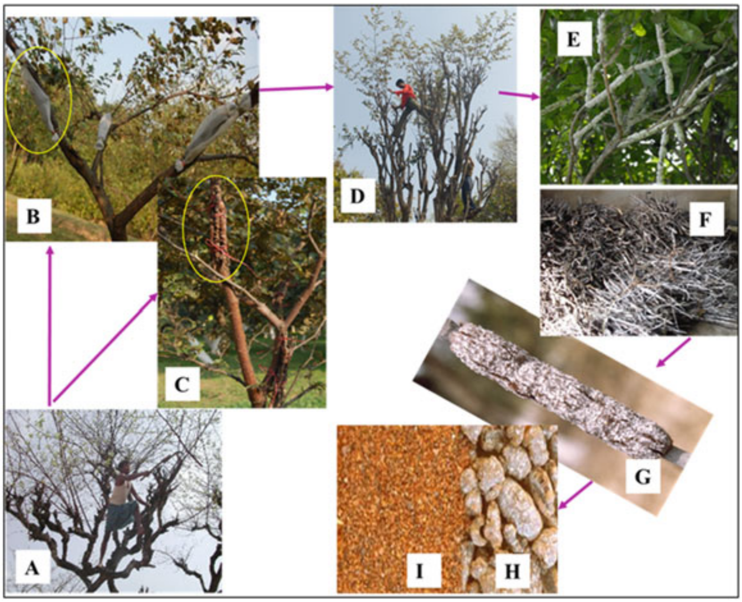

Fig. 14.2 Management practices of lac farming. (**a**) pruning of lac host tree, (**b**) improved inoculation of broodlac, (**c**) traditional way of inoculation of broodlac, (**d**) harvesting of lac, (**e**) lac encrustation, (**f**) harvested lac stick, (**g**) lac stick, (**h**) scraped lac, (**i**) seedlac. Photo courtesy: AK Jaiswal

Table 14.1 Crop management schedule for different lac strains

Insect biotype	Strain	Croping season	Inoculation month	Harvesting month	Duration
Bivoltine	Kusmi	Aghani (winter)	June/July	Jan/Feb	6 months
		Jethwi (summer)	Jan/Feb	June/July	6 months
	Rangeeni	Katki (rainy)	June/July	Oct/Nov	4 months
		Baisakhi (summer)	Oct/Nov	June/July	8 months
Trivoltine		Winter	Oct/Nov	March/April	5 months
		Summer	March/April	July/Aug	4 months
		Rainy	July/Aug	Oct/Nov	3 months

and dewaxed-decolourized lac (Baboo and Goswami 2010). The resin is a polyester type of material, comprising basically long-chain and sesquiterpenic fatty acids, better categorized as oligomer used in various industrial sectors such as food, varnishes, lacquers, paints, cosmetics, jewellery, adhesive, electrical and electronics, pharmaceuticals, firecrackers, handicrafts and preparation of bioactive compounds such as insect sex pheromones, plant growth regulators, insect repellents and

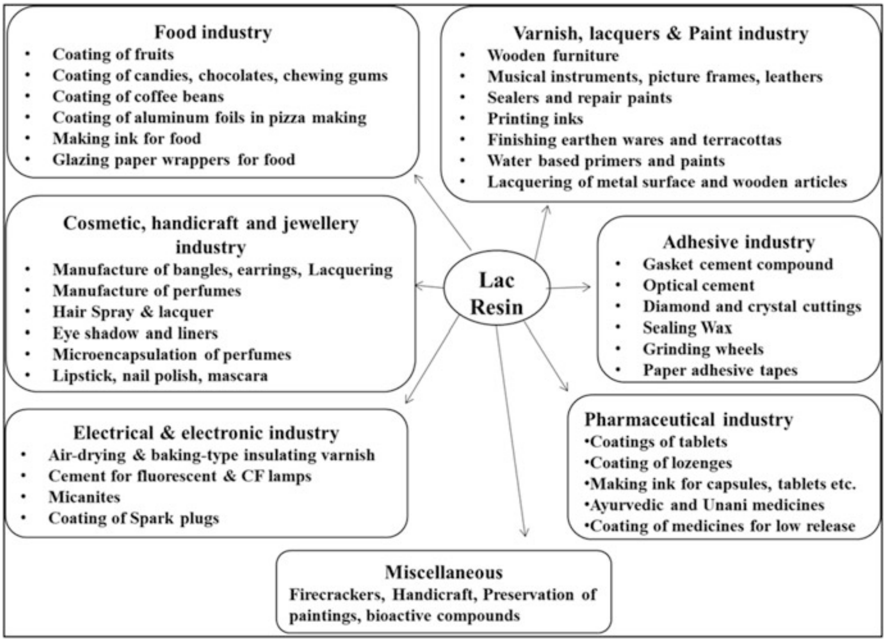

Fig. 14.3 Commercial usage of lac resin

nematocides (Fig. 14.3) (Goswami and Sarkar 2010). The lac dye, a polyhydroxy anthraquinone derivative, is used for brightening and strengthening of silk and wool while dyeing. Lac wax is an important component of floor polishes and cosmetics (Sarkar 2011). The aleuritic acid, isolated from lac, is utilized for synthesis of high-value perfumery compounds such as isoambrettolide, ambrettolide, civetone and exaltone (Sarkar 2013). India is the largest producer of lac in the world with a production of 20,000 tons, and shellac, seedlac and aleuritic acid are the highest exported commodities.

14.3.3 Socio-economic Aspects

The production, processing and value addition in lac are a potential source of income and employment generation in Jharkhand and Chhattisgarh tribals mostly forest dependent. Around 177 lac processing units are present in the country which employs 3–4 million people (Table 14.2). Around 40% tribal women of five major lac producing districts derive employment in this sector (Jaiswal 2012). To avoid quality deterioration due to polymerization and aging under storage condition of the resin, lac is generally processed at villages as cottage industries generate 50–167 days of employment (Fig. 14.4). The net annual income (profit) per hectare is in the range of INR 21,000–77,800 (US$300–1110) depending on the tree species and their number (Table 14.3).

Table 14.2 Lac producing and processing states in India

States	Districts (centres)	No. of processing units	Products made
Chhattisgarh	Dhamtari	15	Seedlac, button lac, bleached lac
	Janjgir-Champa (Sakti)	5	Seedlac, shellac, bleached lac, dewaxed shellac, lac dye
	Kanker	2	Seedlac
	Korba (Kathgora)	7	Seedlac, shellac, bleached lac
	Rajnandgaon	1	Seedlac, shellac
	Raipur	1	Bleached lac, aleuritic acid
	Daltonganj	2	Seedlac
	Ranchi (Khunti, Bundu, Murhu)	10	Seedlac, button lac, shellac, lac dye, bleached lac
	Simdega	2	Seedlac
	Saraikela-Kharsawan (Chandil)	1	Bleached lac
	W. Singhbhum (Chakradharpur)	1	Shellac
West Bengal	Purulia (Balarampur)	93	Seedlac, shellac, button lac, bleached lac, aleuritic acid, lac wax, dewaxed-decolourized lac
	North 24 Pargana	1	Seedlac, shellac, button lac
	Others	20	Seedlac, button lac
Maharashtra	Gondia	6	Seedlac, shellac, button lac
Others		10	

14.4 Traditional Agroforestry Systems

Traditionally lac is cultivated by tribals of Central and Eastern India in forest and sub-forest areas. In sub-forest areas the lac cultivation is practiced either on community lands or on lands owned by the farmers. It has been observed that many a time a single tree is owned by different persons and they cultivate lac on different parts/ sides of the tree.

A few case studies conducted in the tribal belt of Chhattisgarh, Jharkhand and West Bengal states of India revealed that the agroforestry activity is well time-honoured in these areas, providing livelihood, in drought condition, and additional opportunity of employment at industry level. Such cultivation on sub-forest trees has prevented deforestation, conserved insect biodiversity and provided firewood (Jaiswal et al. 2002). The farmers have subsistence rainfed farming and follow their traditional ways for lac cultivation on the *Z. mauritiana*, *B. monosperma*, etc. trees bordering paddy field. They depend on self-multiplying lac insects and harvest

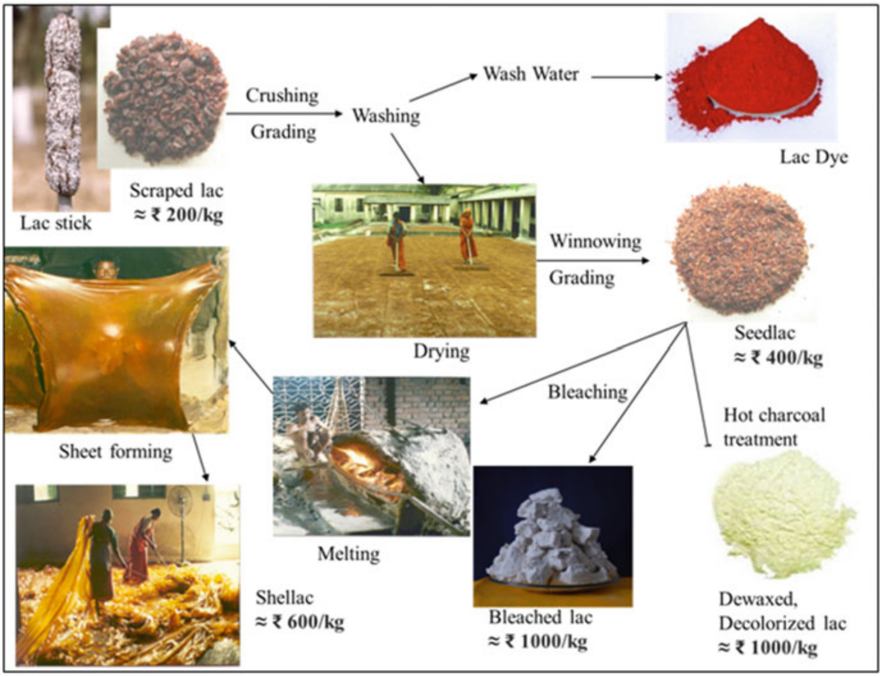

Fig. 14.4 Lac processing cottage industry and various products. Photo courtesy: AK Jaiswal

Table 14.3 Estimated cost of sticklac production at cottage-level industry

	B. monosperma	*Z. mauritiana*	*S. oleosa*	*F. semialata*
Number of trees/plants	100	100	10	1000
Man-days employed	80	167	50	40
	Amount (₹)			
Non-recurring expenditure	15,800	23,000	25,000	60,000
Recurring expenditure	26,000	54,000	26,000	11,000
Expenditure per annum	64,000	98,000	54,000	19,000
Income per annum	87,000	144,000	75,000	55,000
Profit per annum	23,000 53,000[a]	45,800 77,800[a]	21,000 41,000[a]	36,000 44000[a]
Net return	136%	147%	137%	288%

[a]In the case of family labour participation

mature lac encrustation suitable for marketing. Their activity is mainly lac collection rather than cultivation. The over-exploitation of trees and lack of healthy seeds are actually adversely affecting the production.

14.5 Technological Interventions

In the traditional lac cultivation, farmers were not able to harvest good crop. The primary causes of the reduced production are continuous exploitation of the same plant over the years and self-colonization of lac insects. Lac cultivation from the same plant results into losing of tree vigour, and self-colonization of lac insects induces build-up of their predators.

As the production largely depends on the host species, type of insect and waiting period between two consecutive crops, self-sufficiency in quality broodlac (seed) and in controlling losses from diseases and pests have been worked out to enhance benefit from this endeavour. In this regard, scattered lac host trees in forest and sub-forest areas such as in farmers' field or in community land were divided into sets or groups for periodical inoculation, so that vigour of host trees can be restored. Relay pruning based on the tree species was introduced for quicker shoot growth. The number of plants on the border and maintaining the distance between the trees in improved lac cultivation practices were introduced to the farmers, and farmers were encouraged to grow rice along with other short-duration crops such as turmeric/*Colocasia* (kharif)/foot yam (rainfed)/brinjal, French bean, tomato (rabi irrigated)/mustard, etc. in their fields (Fig. 14.5) (Jaiswal and Singh 2012).

The supply of high-quality seeds to the farmers is channelized, and trainings are imparted to produce for their own and market requirement as well. Apart from general practices of lac cultivation, the crop protection plays an important role for sustainable crop production. The integrated pest management strategy for major insect pests has been established (Jaiswal 2009; Jaiswal and Singh 2013, 2014d, 2015; Singh et al. 2013, 2014; Jaiswal et al. 2017, 2018).

14.6 Developed Agroforestry Systems

Several agroforestry models, based on the cropping intensity and capacity of host trees to sustainable lac production, were developed at IINRG, Ranchi, Jharkhand and elsewhere in the country (Jaiswal and Bhattacharya 2007; Jaiswal and Singh 2014a, b, c). Plantations may be designed as single-species block plantation or multi-tier multi-species plantations, depending on the geographical and climatic conditions.

14.6.1 Block Plantation

The major host plants such as *S. oleosa*, *B. monosperma*, *A. auriculiformis*, *A. lucida*, *A. catechu*, *A procera*, *Calliandra calothyrsus*, *D. sissoo*, *Z. mauritiana* and *F. semialata* are planted in blocks (Fig. 14.6). The block plantation may be designed for (a) dual crop (winter and summer crop) cultivation, for example, *S. oleosa*-, *B. monosperma*- and *A. lucida*-based agroforestry; (b) single winter crop cultivation, for example, *F. semialata*- and *A. catechu*-based agroforestry;

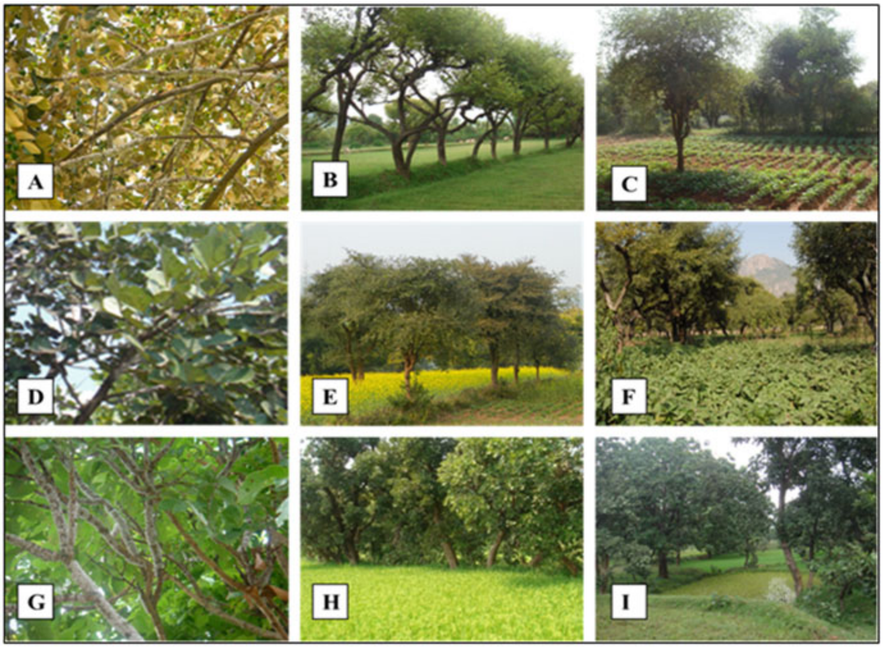

Fig. 14.5 Traditional lac-based agroforestry systems. (**a**) lac encrustation on shoots of *Z. mauritiana*; (**b**) *Z. mauritiana* trees on border of paddy field; (**c**) potato farming along with lac cultivation on *Z. mauritiana*; (**d**) lac encrustation on *B. monosperma* twigs; (**e**) mustard crop along with lac cultivation on *Z. mauritiana*; (**f**) brinjal (*Rabi*) cultivation under tree of *Z. mauritiana*; (**g**) lac encrustation on branches of *Schleichera oleosa*; (**h**) *B. monosperma* trees on border of paddy field; (**i**) a small paddy field in between scattered trees of *B. monosperma* with lac. Photo courtesy: AK Jaiswal

(c) single crop, but under special circumstances the other crop can also be taken, for example, *Z. mauritiana*-based agroforestry; and (d) systems for dual crop but utilized for specific purpose (brood preserver), for example, *Ficus spp.*-based agroforestry.

The planting and the management practices (Table 14.4) need to be followed. For sustained yield and good crop vigour, the trees should essentially be divided into two groups in each block. This aids in synchronized inoculation and maintenance and for round-the-year production, viz. summer (October/November–June/July) and rainy season crop (June/July–October/November) in a cycle of 5–6 years. At harvesting healthy trees and branches are marked for broodlac marketed as seed for new crop, while infested or damaged branches are harvested in summer as *ari* (harvestable immature) crop.

Fig. 14.6 Developed lac-based agroforestry systems. (**a**) *Butea monosperma*, (**b**) *Ziziphus mauritiana*, (**c**) *Schleichera oleosa*, (**d**) *Flemingia semialata*, (**e**) *F. semialata* + brinjal, (**f**) *F. semialata* + papaya. Photo courtesy: AK Jaiswal

14.6.2 Mixed and Multi-Tier Plantation

Two or more host tree-based agroforestry systems are promoted for the places, where mortality of lac insects due to high summer heat is frequent and that cause shortage of broodlac. For these places, incorporation of suitable summer host tree along with usual trees is crucial. *Ficus* species (*Ficus glomerata* (dumber), *F. infectoria* (pakur), *F. glabella* (putkal), *F. cunea* (porho), *F. religiosa* (Pipal), etc.), etc. are recommended for this purpose (Table 14.5) (Jaiswal and Singh 2012, 2014b). The summer host trees may be planted in blocks, or they may be interspersed with winter host trees at recommended distance or trees at bunds, or common lands may be used for the purpose.

14.6.3 A Successful Multi-Tier Agroforestry Model

Traditional lac host plants are mostly slow-growing medium-size trees. These plants have limitations such as they take about 5–15 years of growth for optimum lac production, difficulty in implementation of cultivation operations, management and harvesting, etc. One *F. semialata*-based multi-tier perennial system was developed.

F. semialata, a leguminous bush of approximately 3–3.5 m in height, can be propagated through seeds, and inoculation of broodlac and harvesting can be done easily. Unlike traditional host trees, lac production on *F. semialata* may be started within a year of cultivation. The intercropping of cereals, short-duration fruit and vegetables crops provided extra remuneration to the farmers. The system was proved successful among the tribals of Jharkhand state of India, for stress-free management and prompt production.

Table 14.4 Management practices of lac host trees

	Schleichera oleosa	*Butea monosperma*	*Ziziphus mauritiana*	*Flemingia semialata*
Habitat	Light well drained, boulder and sand-stone beds also found in ravines and loamy soils	Grassland, community lands, poorly drained saline soils	Wastelands grow on variety of soil such as laterites, sandy or alluvial or arable, well drained	Prefers well-drained soil rich in organic matters
No. of trees	100 ha^{-1}	625 ha^{-1}	400 ha^{-1}	10,000 ha^{-1}
Spacing	10×10 m	4×4 m	5×5 m	1×1 m
Layout	Row planting			Row planting (triangular pattern)
Age of tree for lac inoculation	15 years	8–10 years	5–6 years	2 years
Grouping of trees for cyclic inoculation	5	2 (for broodlac) 3 (for broodlac + sticklac)		
Time of pruning	January/February or June/July	April	May or February	January/February
Time of inoculation	18 months after pruning	6 months after pruning	6 months after pruning	6 months after pruning
Brood (seed) rate	4–8 kg/medium-sized tree	250–350 g per tree (for broodlac) 1 kg per tree (for sticklac)	2.0 kg per average-sized tree	300 kg ha^{-1}
Harvesting	• Partial harvesting: Six months after inoculation • Complete harvesting: A year after the inoculation, i.e. January/February or June/July	• Broodlac harvesting: 1 year after inoculation in October after allowing self-inoculation in July • Sticklac harvesting: April/may	May or February	January/February

Table 14.5 Multispecies agroforestry systems of lac production

Tree species	Seasonal lac crop
A. catechu + *S. oleosa*/*A. lucida*	Rainy crop of *rangeeni* lac Winter crop of *kusmi* lac
A. lucida (Galwang) + *Z. mauritiana*/*F. semialata*	Winter and summer crop of *kusmi* lac
Z. mauritiana + *S. oleosa*	Winter crop of *kusmi* lac
Z. mauritiana + *B. monosperma*	Summer crop of *rangeeni* lac Rainy crop (*rangeeni*) for broodlac
Z. mauritiana + *Ficus spp.*	*Rangeeni* lac and summer broodlac
Z. mauritiana + *Albizia spp.*	Summer and winter crops of *kusmi* lac
F. semialata − *S. oleosa* − *A. lucida*	Winter crop of *kusmi* lac in annual rotation of host tree
F. macrophylla/*F. semialata*/*P. serratum* + *S. oleosa*	Winter crop of *kusmi* lac

Design and Management

In this system, tree species such as *F. semialata*, *S. oleosa* and *Z. mauritiana* serve as the perennial component of system, while integrated ground vegetables and fruit crops are the annual component (Fig. 14.7) (Kumar 2013; Jaiswal et al. 2015; Bhat et al. 2016). Lac is cultivated on *F. semialata*, *Z. mauritiana* and *S. oleosa*. The fruit plants such as aonla (*Emblica officinalis*), guava (*Psidium guajava*), lime (*Citrus aurantifolia*) and mango (*Mangifera indica*) may be planted at suitable distance in *Z. mauritiana* rows, depending on the grower's need and choice. The selection of vegetables depends on the season and on the choice of growers. However, the recommended agronomic and plant protection practices are required for good growth and optimum yield.

The designing of the system was based on the plant type, height, root system and canopy pattern, inflicting least spatial-temporal interactions. The *S. oleosa* planted at 10.0×15.0 m ($\approx$ 60 trees ha^{-1}), *Z. mauritiana* planted at 5.0×2.0 m spacing ($\approx$ 1000 plants ha^{-1}) and *F. semialata* with 1.0×1.0 m in paired rows ($\approx$ 8000 plants ha^{-1}) are recommended for the optimum land utilization. In the establishment phase of the system, other fruit trees such as papaya (*Carica papaya*) may be planted in between *S. oleosa* and *Z. mauritiana* plants.

The lac production starts from the second year on *F. semialata.* From the fifth year onwards, lac production began on *Z. mauritiana*, and from the tenth year onwards, *S. oleosa* plants are used for cultivation. This in all provides an average income from lac of about 0.3 million ha^{-1} annum^{-1} Indian rupees in the initial 5 years of plantation, about INR 0.7 million ha^{-1} annum^{-1} during the subsequent 5 years and INR 1.0 million ha^{-1} annum^{-1} from the tenth year onwards. The additional income from seasonal fruits and vegetables may be around INR 0.05 million ha^{-1}annum^{-1}, depending on the market rates.

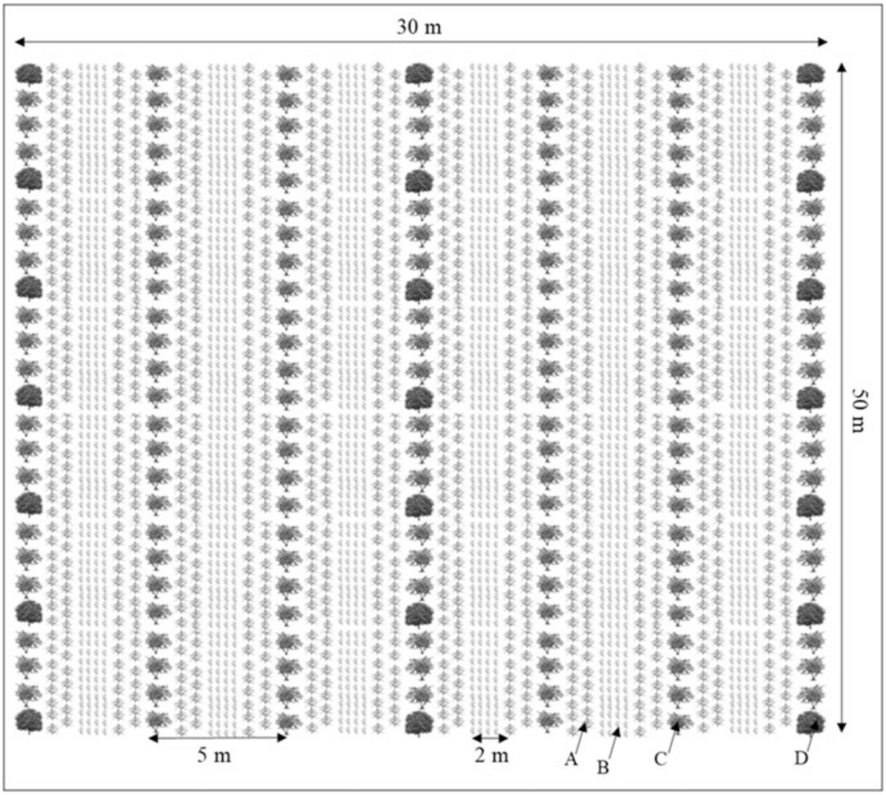

Fig. 14.7 Design of multispecies plantation for lac cultivation. (**a**) *F. semialata*, (**b**) vegetable crop, (**c**) *Z. mauritiana*/fruit plants, (**d**) *S. oleosa* + fruit plants

14.7 Conclusion

Opportunities for farm and tribal communities exist for transforming the traditional lac-based agroforestry into modern remunerative venture from degraded lands. The improvisation in traditional models described as a result of decades of research and development efforts will provide sustainable farm income. The agroforestry models incorporating crop (vegetable, fruit) component in between the interspaces provide additional income to the marginal farmers of the tribal belt of India. This may act as a buffer in case of failure of the main product (lac) on account of some unpredictable and uncontrolled factors in a given season.

The commercial opportunities in view of prevailing market orientation should be explored by the farmers as well as the tribes towards intensive deliberate management systems that yield quality products from priority species that meet market requirements. A four-pronged approach that involves improvements in quality and quantity of products; sorting, grading and packaging; transforming product from raw to semi-processed state; and in-depth market analysis is needed. The lac-based agroforestry has another important dimension as the lac growers protect host trees in wasteland and community lands and thus, contributes in arresting the trend of forest degradation.

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The Role of Insects in Enhancing Ecosystem Services of Tree-Based Systems on Degraded Lands

15

Cathy Dzerefos, Afton Halloran, and Luiza de Sousa

Abstract

Worldwide, agroforestry has been shown to provide farmers and communities with a range of direct services such as food, livestock feed, wood and medicine as well as indirect ecosystem services such as pollination, pest and weed control and soil formation and enrichment. These multiple benefits suggest that woody perennials, such as trees and shrubs, could contribute to a regenerative agricultural landscape that lessens poverty and malnutrition in marginalized communities. In this chapter, we review beneficial insects and their ecological significance in human-modified landscapes. Insects should not be written off as insect pest species by the education, agricultural or policy sectors. Rather, the ecosystem services provided by beneficial insects and their associated habitat should be left intact in agricultural and urban settings. In the case of insects that are both beneficial and harmful to food production, their promotion as food to areas where insect cuisine is unknown in conjunction with sustainable farming methods should be considered.

Keywords

Ecosystem services · Beneficial insects · Human-modified landscapes · Woody perennials

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15.1 Introduction

Agriculture is a significant anthropogenic activity that has removed natural vegetation, increased species extinction rates, altered biogeochemical cycles and changed the global distribution of plants and associated pests (Lewis and Maslin 2015). After 11,000 years of cultivating the soil and implementing a diversity of methods to grow food (Lewis and Maslin 2015), the collapse of insect populations is threatening global food security (Hopwood 2008; Dietemann et al. 2009). The most studied ecosystem services provided by insects to agriculture are pollination and soil enrichment (Noriega et al. 2018). Armed with the knowledge of ecosystem functioning, the Global Partnership on Forest Landscape Restoration and the International Union for Conservation of Nature (IUCN) are promoting the Bonn Challenge on a global scale (www.bonnchallenge.org). They aim to rehabilitate the ecology of 350 million hectares of degraded and deforested land by 2030. Multifunctional agroforestry landscapes are defined by the trees and shrubs that are found in areas situated between formal farming activities. The trees and shrubs may produce nutritious edible fruits or insects, dry season feed for livestock, fuelwood (Everson and Underwood 2004; Dzerefos et al. 2009), construction materials and medicine (Cunningham and Shackleton 2004).

The beneficial role of insects in agroforestry has been overshadowed by the adverse effects of insect pests that result in crop losses or failure (Noriega et al. 2018). It has been estimated that the value of insect-derived ecosystem services in the US is US$57 billion (Losey and Vaughan 2006). It is not only woody perennials such as trees and shrubs that are important for beneficial insects; natural grasslands left between maize crops have been found to constitute a significant source of arthropods, including beneficial insects (Cook et al. 2007; Botha 2017). To encompass the services provided by trees as well as grasses, the agroforestry should rather be referred to as an agroecosystem. An agroecosystem is likely to have more pest parasitoids and predators than actual crop pests (Van Huis et al. 2013) that can be optimized for biological control.

Research into livelihoods in many impoverished areas of Africa (Ashiru 1988; Dovie et al. 2002; Egan 2013; Halloran 2017), Asia (Megu et al. 2018; Halloran et al. 2016), Central and South America (Van Itterbeeck and Van Huis 2012) and Australia (Van Huis et al. 2013) highlights the importance of entomophagy as a prominent ecosystem service on which agroforestry could capitalize. Indigenous knowledge systems (IKS) contain knowledge acquired over generations on locating, preparing and sustainably harvesting edible insects. In most cases, edible insects that are freely collected from communal land used for grazing and subsistence agriculture (Dovie et al. 2002; Egan 2013), provide a good source of protein and micronutrients important for the growth of children (Dube et al. 2013; Dzerefos and Witkowski 2014; Roos 2018). There has been increased interest amongst Western scholars regarding the use of insect protein for direct human consumption and animal feed (Chaalala et al. 2018), which has led to concerns that marginalized poor people may experience restricted access to insects in the future (Schiemer et al. 2018).

15.2 Biodiversity of Insects in Tree-Based Systems

15.2.1 Insects on Edible Fruit Trees

Fruit trees such as the marula (*Sclerocarya birrea*) and the baobab (*Adansonia digitata*) have for centuries been conserved following the IKS of local communities and have become iconic in the African agroforestry landscape. Marula (Shackleton et al. 1997) and baobab (Hellekson 2009) trees have been revered by communities for their fruit, medicinal uses and spiritual significance. The marula fruit is used to produce a seasonal fruit beer, which is shared amongst neighbours and friends (Shackleton et al. 1997). Commercial production of marula liqueurs and jams has encouraged cultivation trials (Cunningham and Shackleton 2004) to increase fruit availability. Similarly, production of cosmetics and health food using baobab products such as seed oil and powdered fruit pulp has led to natural recruitment of new trees being a concern (Venter and Witkowski 2013; Gebauer et al. 2016). Wild-sourced marula and baobab fruits provide a source of income in areas where agriculture is constrained by low, unpredictable rainfall and lack of capital (Shackleton et al. 1997; Venter and Witkowski 2013).

In the semi-arid environment of Bushbuckridge, South Africa, over half the households sampled in nine villages cultivated marula trees (Shackleton et al. 1997). Further north in Vhembe, more baobabs were found in homesteads and cultivated fields than in natural areas (Venter and Witkowski 2013). Baobabs in Sudan and Kenya have been planted as avenue trees in towns and left amongst sisal (*Agave sisalana*) plantations and other crops (Gebauer et al. 2016). Cousins and Witkowski (2015) described marula and baobab trees as keystone species, meaning that ecosystem function centres around their presence in a landscape. In arid environments, baobab tree cavities can host biodiversity such as spiders, termites and wasps (Hellekson 2009), and these may offer ecosystem services to adjacent farming activities. Marula and baobab provide seasonal food to birds, monkeys, insects and other fauna, mainly through their flowers, leaves and fruits. Moreover, prey species are also attracted to food and shelter provided by the trees. As several insects are attracted to the food source, there is greater opportunity for breeding.

Nutrient-poor coastal sands of Mozambique support trees such as the African medlar (*Vangueria infausta*) and four species of monkey orange (*Strychnos*) (Cunningham and Shackleton 2004). These trees are likely to have been conserved by local subsistence farmers for their fruit and shade, but further research is required to understand coexisting biodiversity, ecosystem services, food webs and impact on crop production.

15.2.2 Insects on Border Plants

Hedgerows are a conglomeration of wild-growing shrubs and occasional trees found along roads or field borders. In the United Kingdom (Samways 1994) and the USA (Hopwood 2008), hedgerows have been identified as sanctuaries for biodiversity that should be encouraged. In Africa, hedges are often planted around gardens or homesteads for aesthetics or as a thorny barrier (live fences). Some thorny plants produce copious flowers and will be discussed further under pollination. Hedgerows are recommended for maize crops grown in areas with good rainfall, but competition for soil nutrients may need to be monitored (Everson and Underwood 2004). Hopwood (2008) recommends enhancing habitat and ecosystem services of insects by planting indigenous vegetation along the roadside network. Remnants of indigenous vegetation might also exist in the agricultural landscape around large termite mounds (termitaria) or rocky outcrops. Termitaria and rocky outcrops provide important insect refuge.

15.3 Ecosystem Services of Insects

15.3.1 Pollination

The African continent is estimated to contain over 310 million wild honeybee colonies, most of which nest in tree hollows (Dietemann et al. 2009). As the African beekeeping industry relies entirely on wild-sourced swarms to populate domesticated hives (Dietemann et al. 2009), sustainability is closely linked to the availability of vegetation for nesting sites and food. The cumulative threats of drought, honey harvesting, habitat loss, pests, pesticides and diseases could escalate in Africa and cause honeybee colony collapse as has been experienced in North America and Europe (Hopwood 2008; Pirk et al. 2016).

Honeybee populations provide important pollination service for agriculture, but the impacts of pesticides on honeybees are not sufficiently researched (Pirk et al. 2016) or controlled (Pace 2018). Recently, numerous beekeepers lost hives due to ant pesticides used in vineyards in the Cape Winelands of South Africa (Pace 2018). Honeybees require year-round sources of pollen and nectar (Munthali and Mughogho 1992). Since global honey production began to decline, honeybees have become a societal concern (Hopwood 2008; Dietemann et al. 2009), and bee deaths are reported and investigated (Pace 2018). Teaching materials to support learning about honeybees are available online and have encouraged schools to keep beehives and to plant pollinator forage (Whitehead 2011).

Landowners are more likely to plant trees and shrubs for uses other than plant forage for pollinators. For example, the Kei apple (*Dovyalis caffra*) is a thorny, edible fruit-producing plant, which can be pruned to form an impenetrable hedge. It has been cultivated in South Africa, Israel and in the suburbs of Nairobi, Kenya, to deter trespassers from entering private property (Cunningham and Shackleton 2004). Honeybees and butterflies feed off the copious nectar produced by Kei apple flowers (Cunningham and Shackleton 2004) and would be locally available to pollinate crops. Truncheons of African coral tree (*Erythrina caffra*) are frequently planted as fences in southern Africa to delineate property or control movement of cattle or pigs (Fig. 15.1). These living fence posts may sprout leaves and roots. During the dry winter months, the truncheons can produce prolific nectar-bearing flowers that attract

Fig. 15.1 Living fence posts of *Erythrina caffra* (African coral tree) flowering (red flowers) in Ga-Modjadji, Limpopo Province, South Africa. An exotic, thorny *Euphorbia* species is flowering (pink flowers) at the base of the posts (Photo: Cathy Dzerefos)

birds and insects (Martin 2010). Such a food source would be beneficial to honeybees, particularly as other flowering plants would be scarce at this time.

Vachellia (*Acacia*) *karroo* (sweet thorn), *Leucaena leucocephala* (river tamarind) and *Gleditsia triacanthos* (honey locust) are planted as fodder-producing trees for livestock (Everson and Underwood 2004) as well as for erosion control. The sweet thorn produced 530–1000 kg ha^{-1} of fodder per year and is available during the dry season when nutrition from grasses is low (Everson and Underwood 2004). The sweet thorn and other thorn trees are rich in pollen, and honey made from them has a recognizable taste and is marketed as *Acacia* honey. River tamarind produces flowers throughout the year and is a reliable food source for honeybees (Orwa et al. 2009).

15.3.2 Role of Insects as Soil Engineers

Two edible insect groups, the dung beetles (Scarabaeidae) and the termites (Termitidae) (Van Huis et al. 2013), modify the biophysical nature of soil (Muller and Ward 2013) in pastoral and subsistence farming areas. It is estimated that Africa carries at least 100 million cattle (Scholtz and Mansell 2009) that are kept for meat, milk and skins and to generate income. In many southern African groups, a bride price or *lobola* will be paid in cattle and goats. Unburied dung produced by cattle, goats and donkeys can result in reduced quality and quantity of grass feed as well as increased levels of coprophagous or dung-feeding flies (Nichols et al. 2008; Scholtz and Mansell 2009). A landscape mosaic of trees, shrubs, grassland, termitaria or fire break between planted crops or urban areas (Fig. 15.2) can offer a solution by harbouring dung beetles. Dung beetles consume or bury unsightly waste within the ground and aerate and enrich the soil with nutrients and thus contribute to improved soil microbial activity and soil chemistry which benefit plant growth (Nichols et al. 2008; ARC 2013; Noriega et al. 2018). Manure exposed to sunlight and air loses nitrogen content, while burying it allows minerals to be released into the

Fig. 15.2 Indigenous forests, a young pine plantation, subsistence agroforestry and grassland pasture create functional ecosystems in Vhembe District, Limpopo Province, South Africa (Photo: Cathy Dzerefos)

soil for plant production (Van Huis et al. 2013). A cow produces about 9000 kg of dung annually, of which approximately half will be used as fuel for fires, for construction, or to fertilize crops (Scholtz and Mansell 2009).

Dung beetle's activities reduce parasitic infection in domestic animals and wildlife by consuming or burying parasite eggs deposited in manure (ARC 2013). The role of dung beetles in cleaning up human faeces not contained in a closed sanitation system should also be classed as an ecosystem service, as this activity reduces the risk of diarrhoea and other diseases in human settlements. Furthermore, dung beetles help to sow seeds that were consumed and egested in the manure, thus acting as a secondary seed disperser (Nichols et al. 2008). It has been suggested that the earth-moving activities of dung beetles, ants and termites reduce soil compaction associated with livestock trampling, thereby increasing the carrying capacity of the land (Losey and Vaughan 2006).

Dung beetles occupy a narrow climatic niche as they require at least 250 mm mean annual precipitation and a mean annual temperature above 15 °C to persist (Scholtz and Mansell 2009). The dung beetle's rainfall requirements coincide with the pasture requirements of cattle, but smaller livestock such as goats and sheep can survive greater aridity. A deficit of dung beetles in areas otherwise suitable for their occurrence may indicate habitat disruption or irreversible modification of ecosystem services (Nichols et al. 2008), possibly arising from excessive use of pesticides or large-scale removal of natural vegetation. The important role of dung beetles in the biological control of flies in the US and Australian cattle industry is reviewed in depth by Losey and Vaughan (2006).

Termites cultivate lignin-digesting fungi in underground, temperature-controlled chambers, thereby releasing nutrients from grass and wood (Davies et al. 2016) and restoring degraded soil. Organic carbon and nitrogen content in termitaria (earth mounds made by termites) are higher than in surrounding soils (Muller and Ward 2013) which validates traditional farming practices to cultivate termite modified soil. In Limpopo Province soil from termitaria is sold at informal markets as a dietary supplement during pregnancy and lactation (Netshifhefhe et al. 2018). Termites excavate deep soil layers in the savannah ecosystem, are associated with increased tree diversity (Davies et al. 2016) and support the growth of edible mushrooms (Van Huis et al. 2013). A study in the Kruger National Park of South Africa measured a cooler microclimate for *Macrotermes* termitaria in relation to the surrounding landscape which made them sought-after resting places for heat-sensitive species (Joseph et al. 2018). This finding could be used by livestock farmers in areas prone to heatwaves.

15.4 Biological Control of Pests

In the US, it is estimated that the cost of biological control of pests from insects is in the region of US$4.5 billion annually (Hodek et al. 2012). In agroecosystems, entomophagous insects serve as parasitoids or predators to control phytophagous crop pests (Sullivan 1987; Noriega et al. 2018). Insects used as biological control agents may require trees to oviposit (lay eggs) and for shelter during the winter (Hodek et al. 2012). Predatory species that are useful to mankind are found within the Coleoptera (beetles), Diptera (flies), Hemiptera (true bugs), Hymenoptera (wasps and ants), Neuroptera (lacewings and ant lions) and Odonata (dragonflies) (Van Huis et al. 2013). Some predatory insects also consume weed seeds amongst crops when the insect food source is exhausted (Phillips 2017).

Some species of Coleoptera, Diptera and Hymenoptera can be secondary parasitoids or hyperparasitoids, thereby influencing the primary parasitoid (Sullivan 1987). For example, the primary parasitoid for the cassava mealybug (*Phenacoccus manihoti*) that was introduced as a biological control agent to protect the cassava plant (*Manihot esculenta*) is influenced by about 110 other insects (Sullivan 1987). Although biological control food webs can be highly complex, they do have the advantage of allowing crops to be grown organically and, in the long term, are more cost-effective than a reliance on pesticides (Van Huis et al. 2013). Pesticides have short-term success in controlling pests but create dependency since the natural enemies of the pest are destroyed. Many species of lady beetles (Coccinellidae) are used in biological control of soft-bodied insect pests such as aphids, mites and scales (Hodek et al. 2012).

Weaver ants (*Oecophylla* spp.) are dependent on host trees to construct elaborate aerial nests. The workers construct nests by weaving together leaves with larval silk (Fig. 15.3). Weaver ants prey on small insects and are sometimes used by mango, cashew, pomelo, lychee and orange farmers in China, South East Asia, northern Australia and sub-Saharan Africa as a natural biological control agent (Diamé et al. 2017). A study conducted in Thailand and Vietnam indicated that citrus yields were similar in ant-protected and chemically protected plots. The cost of using ants was lower than the cost of spraying insecticides and led to net income gains of 15% in Thailand and 47% in Vietnam (Offenberg et al. 2013). As there is a growing demand by health and environmentally conscious consumers for organically grown products and sustainable agricultural practice, there may be further growth in the application

Fig. 15.3 Arboreal weaver ants starting to construct a nest, Khon Kaen Province, Thailand (Photo: Afton Halloran)

of weaver ants in fruit production. Weaver ant larvae and pupae are also a food source and can be sold to supplement income (Sribandit et al. 2008).

Ripening indigenous fruits from trees and shrubs may attract a range of insect feeders such as Diptera, Hymenoptera and Lepidoptera (De Lange et al. 2005). Fruits might be useful in developing a cost-effective 'push-pull strategy' for insect pest management as they might attract predatory insects as well as insect pests (Cook et al. 2007).

15.5 Edible Value of Insects

15.5.1 Palm Weevil

Indigenous peoples of Africa, Southern Asia and South America have used palm tree products such as palm weevil (Coleoptera: Curculionidae) larvae and the fruit for food; and poles and leaves for construction as well as wine, oil and starch (Van Itterbeeck and Van Huis 2012). In areas where palm weevils are used as food, their population has been controlled by harvesting, but palm trees are damaged through the methods used to encourage their production (Choo et al. 2009). IKS have identified that the South American palm weevil (*Rhynchophorus palmarum*) can be attracted to lay its eggs in young palms where an oviposition site has been gouged out the trunk. The bearded weevil (*Rhinostomus barbirostris*) can burrow into trunks that have not been damaged and are attracted to older flowering palms (Choo et al. 2009). In the Niger Delta of Nigeria, cut palms are left to be infected by *Rhynchophorus phoenicis* and harvested months later (Coultier 2015). In Thailand, cabbage palm or sago palm trunks are cut into 50 cm lengths, and 5 cm holes are drilled to create refuge for the insects (Hanboonsong et al. 2013). Five breeding pairs of *Rhynchophorus ferrugineus,* after 40–45 days will produce, up to 2 kg palm weevil larvae in the prepared trunks. Alternatively, palm weevil breeding pairs can be fed a mixture of ground palm stalk and pig feed (Hanboonsong et al. 2013). This controlled method of production could encourage year-round availability and prevent unnecessary destruction of natural habitats. The production system could investigate using dead or diseased palm trunks.

15.5.2 Edible Stinkbug

The Natal sand olive (*Dodonaea viscosa* var. *angustifolia*) has been planted extensively in southern Africa for its ornamental value as a glossy, evergreen hedge. The shrub is one of a range of known food and perch plants for the edible stinkbug *Encosternum delegorguei* in South Africa (Dzerefos et al. 2009) but does not produce edible fruit. Malawi and Zimbabwe have a popular fruit-bearing tree *Uapaca kirkiana* (sugarplum) (Cunningham and Shackleton 2004) that hosts edible stinkbugs during the winter months (Mawanza 1999). In South Africa, edible stinkbugs congregate on plantation-grown pine trees, in mango orchards or indigenous trees and shrubs in the mist belt (Dzerefos and Witkowski 2015). The edible stinkbug has a short proboscis, which does not cause damage to crops (Dzerefos et al. 2009); however, timber growers complain that during stinkbug collections the growing points of pine saplings are damaged. Sometimes an entire pine tree or indigenous tree may be felled to access edible stinkbugs (Dzerefos and Witkowski 2015). Similarly, in Malawi, remote sensing showed large-scale felling of trees, which communities confirmed was to collect edible stinkbugs (Mlotha 2001). In South Africa, Malawi and Zimbabwe edible stinkbugs are harvested and eaten as a delicacy or sold to generate household income (Dube et al. 2013; Dzerefos and Witkowski 2015). In various publications on Malawi, *E. delegorguei* (Hemiptera: Tessaratomidae) has erroneously been referred to as *Nezara robusta* (Hemiptera: Pentatomidae), a crop pest (Dzerefos and Witkowski 2014).

15.5.3 Lepidoptera

Egan (2013) documented 11 edible insects and their host plants in the Blouberg area of South Africa. She produced two posters, in English and the vernacular, for teachers to use in schools to encourage sustainable use of the insects and their hosts. The caterpillars of *Hemijana variegata* are specialist feeders on the false turkey-berry (*Plectroniella armata*) and, to a lesser extent, on the porcupine bush, *Pyrostria hystrix* (Egan 2013). The false turkey-berry produces a delicious fruit, and its thorny branches are used as fuelwood and to deter browsing animals from feeding or trampling saplings or crops (Egan 2013). Another under-researched edible caterpillar from this area is *Petovia marginata*, which feeds on a well-known indigenous fruit tree, the African medlar (Egan 2013). The final caterpillar stage of *H. variegata* and *P. marginata* will bury into the ground to pupate. This strategy probably protects the pupa from predators, dehydration and disease but also requires the area to be protected from fire or digging.

The mopane worm known as *Imbrasia belina* is the most popular edible insect in sub-Saharan Africa that is available in fresh or dried form throughout the year

(Akpalu et al. 2009; Dube et al. 2013). Mopane worm is a misnomer as it is not a worm but a caterpillar of the moth family Saturniidae. It occurs in semi-desert, bushveld and grassland biomes of Angola, Malawi, Namibia, Mozambique, South Africa, Zambia and Zimbabwe. Although the mopane worm favours the mopane tree, *Colophospermum mopane*, the caterpillars do occasionally occur on other indigenous trees such as marula and species of *Carissa, Diospyros*, *Ficus*, *Searsia*, *Terminalia* and *Trema* (Makhado et al. 2014; Ditlhogo 1996). Once the caterpillar has undergone four moults and reached full growth, it will crawl down the host tree trunk and burrow into the soil to a depth of 10 cm or more to pupate. Trees may be damaged while harvesting mopane worms (Akpalu et al. 2009; Egan 2013). Examples of habitat manipulation through burning and ploughing management and moving edible caterpillars to selected trees to facilitate a good crop, easy collection and flavour have been documented in sub-Saharan Africa (Van Itterbeeck and Van Huis 2012). During the cool morning harvesters collect mopane worms, then rest in the shade and squeeze out the alimentary canal and its vegetable contents. The waste residue is left on the soil, and nutrients are released as it decomposes. Since the sale of beef decreases during the caterpillar harvesting season, it is claimed that the Pedi people of South Africa prefer caterpillars to beef (Womeni et al. 2009).

To promote the IKS of the mopane worm and its significance, the North-West University has designed a poster for use in schools (Fig. 15.4) which illustrates academic research in an accessible format for classroom use. Similarly, early childhood development programs have been funded by the Korean government to encourage entomophagy, IKS and interest in entomology (Shin et al. 2018).

Wild seringa (*Burkea africana*) is the food plant of the pallid emperor moth (*Cirina forda*). The caterpillars known in the vernacular as *dinata* are a sought-after edible delicacy in South Africa (Egan 2013) and Zimbabwe (Dube et al. 2013). Although Coultier (2015) refers to *C. forda* caterpillars feeding on *Vitellaria paradoxa* (shea tree), the geographical distribution suggests that the species is actually *Cirina butyrospermi*, known to locals as kanni. Populations have declined due to overharvesting of the caterpillars as well as felling of the host tree for housing and agriculture (Toms 2005). In areas that have a history of edible insect collection, education for sustainable development could have an important role to play in local schools where host trees could be planted or grown and then left in situ for the insect life cycle to be completed. Many schools in southern Africa have food gardens to supplement the children's home diets, and these should be designed using agroforestry principles and to double up as an educational resource.

The sundowner moth (*Sphingomorpha chlorea*) has an edible caterpillar that feeds off wild seringa (Egan 2013), and the adult moth is a fruit orchard pest. Collecting the caterpillars and rearing them for consumption or sale provides an opportunity to avoid pesticides as was done with grasshoppers collected from rice fields (Pemberton 1994). The economic viability of collecting insects for food would need to be proven to farmers that are unfamiliar with the potential of entomophagy.

The close interconnection that edible insects have shared over centuries with man, coupled with keen observation, has highlighted the relationship between these insects and the changing environment. For example, increasing frequency of drought

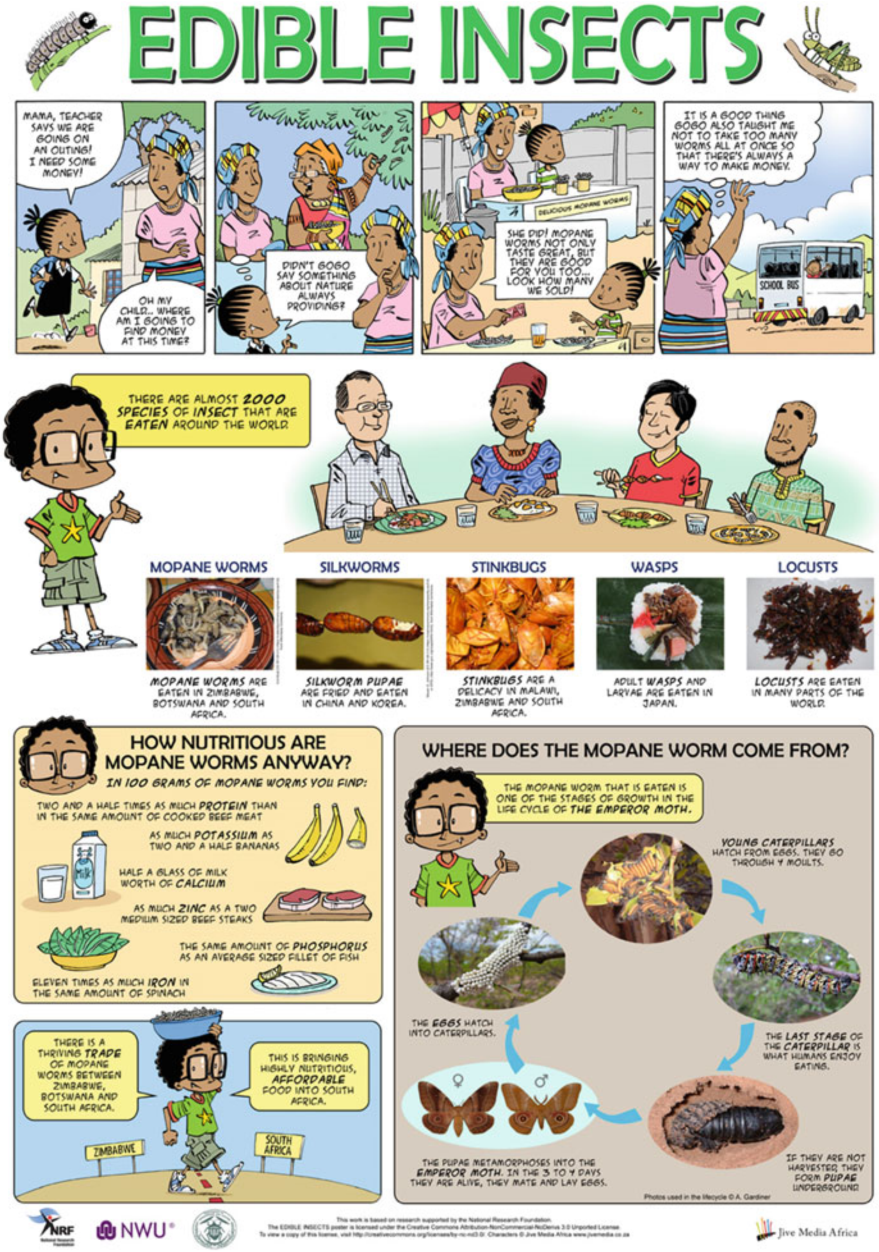

Fig. 15.4 An educational poster to promote entomophagy and awareness of the importance of *Imbrasia belina* (mopane worm) in South African schools

associated with climate change is perceived to decrease the occurrence of mopane worms in Botswana (Joubert 2018) and edible insects in the Blouberg of South Africa (Egan 2013). Similarly, poor harvests of edible stinkbugs have been attributed to drought years (Dzerefos et al. 2013).

15.6 Conclusions

The Anthropocene period is characterized by increasing pesticide use, clearing of land for agriculture, deforestation and extreme climate (Lewis and Maslin 2015) that impact the survival of beneficial insects, their host plants and poor marginalized communities. Since 2005, ecosystem services reliant on insects have gained increased recognition (Noriega et al. 2018), especially in terms of the benefits and opportunities offered by entomophagy (Van Huis et al. 2013; Schiemer et al. 2018). The nutritional value of edible insects requires promotion at the level of school education (Netshifhefhe et al. 2018). Monitoring of host plants that provide insect shelter, water and food and adaptive management of the agroecosystem are required to ensure persistence of beneficial insects. The felling of trees has been suggested as a reason for reduced harvests of various edible caterpillars in Nigeria (Ashiru 1988) and southern Africa (Munthali and Mughogho 1992; Toms 2005; Akpalu et al. 2009) and could be alleviated through the practice of agroforestry and improved education for sustainable development. With agroforestry practices, insects can adapt to habitat alteration, fragmentation or destruction as there are interconnected biotic corridors and reduced edge effects between natural and farmed areas. Working with ecological systems, rather than against them, can reduce costs of production; this has been demonstrated in the use of biological controls rather than of pesticides. The ultimate biological control measure would be to harvest pest species such as palm weevils, grasshoppers and caterpillars in areas of plenty to support global food security (Coultier 2015). A holistic view of the environment and ecosystems can be included in teaching and learning and practiced at the level of the community school through tree and insect appreciation projects and the practice of agroforestry on the school grounds. It is only when such systems thinking is introduced at various levels of a community and a nation that agroecosystems can be achieved.

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Promoting Bamboo-Based Agroforestry for Enhancing Ecosystem Services from Degraded Lands

16

T. Solomon, H. Moon, S. Abebe, A. S. Minale, and Demel Teketay

Abstract

Agroforestry innovations on degraded lands have been prioritized for promoting environmental sustainability, advancing food and fodder security, and achieving United Nations Sustainable Development Goals. Although neglected in scientific research and development, bamboo-based agroforestry has traditionally been managed on family farms because of their great socioeconomic values in rural lives especially in Asia. Recently, there has been increasing interest in their role in soil health improvement, biomass production, and climate change mitigation. However, our knowledge on the contribution of bamboo-based agroforestry for enhancing provisioning ecosystem services is very limited. The aim of this chapter is to compile existing information on social, economic, and ecological implications of bamboo-based agroforestry with an aim to create and advance our understanding on the role of bamboo in enhancing ecosystem services.

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Keyword

Agroforestry · Bamboo-based agroforestry · Forest and landscape restoration · Socioeconomic role

16.1 Introduction

Bamboo is a group of plants that belong to the family Poaceae (Gramineae) and subfamily of Bambusoideae (McClure 1966), comprising approximately 1500 species representing 87 genera (FAO 2005). According to Sungkaew et al. (2009), three main lineages of Bambusoideae, namely Arundinarieae (temperate woody bamboos), Bambuseae (tropical woody bamboos), and Olyreae (herbaceous bamboos), are recognized. Bamboo species are mostly distributed in tropical and subtropical areas of Asia, Africa, and Latin America (Zhou et al. 2005; Zhuang et al. 2015; Thokchom and Yadava 2017), covering 33 million ha and accounting for about 1% of the total area of world forest (Zhou et al. 2011).

According to Zhuang et al. (2015), Asia possesses about 1000 bamboo species, covering over 18 million ha. Most of this comprises natural stands of native species rather than plantations or introductions. With over 500 species, represented in 39 genera, China has the richest bamboo resources in the world in terms of species, area coverage, and reserve of bamboo and has long been known as "kingdom of bamboo" (Zhou et al. 2005). Its bamboo resources cover an estimated area of four million to six million ha (Bystriakova et al. 2003). In the country, bamboo is becoming an industrialized cash commodity with production of a wide range of high-value products (Pérez et al. 2014). Thus, bamboo has played a significant role in China's economic development. From the last three decades onwards, the bamboo industry has been rapidly developed in China (Zhou et al. 2011). Concomitantly, the area of bamboo forests has steadily increased in the country and is currently about 6.72 million ha (Li et al. 2015).

Ethiopia has one of the largest resources of bamboo in Africa. The country possesses about 67% of the continent and 7% of the world total bamboo forest area (Embaye 2000; Endalamaw et al. 2013; Mekonnen et al. 2014). It has two indigenous species of bamboo, *Yushania alpina* K. Schumach (highland bamboo) and *Oxytenanthera abyssinica* A. Richard (lowland bamboo), with an area coverage of one million ha (Embaye 2003; Embaye et al. 2005; Desalegn and Tadesse 2015). Unlike other countries, such as China, India, and Taiwan, the economic return obtained from these vegetation resources is very low, while the utilization is so rudimentary and unsustainable (Mulatu and Kindu 2010; Endalamaw et al. 2013). Currently, the bamboo forests are under high pressure and suffering great depletion. The expansion of agricultural land investments and changing bamboo stands to other land uses, open grazing, and fire hazards are important causes for depletion of bamboos (Bessie et al. 2016; Desalegn and Tadesse 2015).

Currently, forest resources, particularly tropical forests, are experiencing increasing pressure due to the growing population (FAO 2010a, b). The increasing rate of tropical deforestation makes the search for alternative natural resources critical. The characteristics of bamboo make it a perfect solution for the environmental and societal consequences of tropical deforestation (Zhou et al. 2005). The bamboos have intrinsic characteristics of growing rapidly and can fulfil a number of critical ecosystem services (Zhou et al. 2011; Li et al. 2016). They have very crucial ecological and environmental functions in soil and water conservation, land rehabilitation, and carbon sequestration due to their biological characteristics (Zhou et al. 2005; Lobovikov et al. 2009; Li et al. 2015). They are unique in their capacity to meet a wide range of socioeconomic, sustainability, and conservation-focused objectives (Wang et al. 2015; Ling et al. 2016), owing to their rapid growth, ease of propagation, and the range of ecosystem services they provide (INBAR 2010a; Zhou et al. 2011; Nath et al. 2015a, b).

The bamboo represents invaluable plant species for adapting and mitigating climate change. They are characterized by rapid growth and a complex network of rhizome-root system (Lobovikov et al. 2009; INBAR 2010a), which enable them to sequester more carbon than fast-growing tropical and subtropical trees under comparable conditions (Lobovikov et al. 2012; Li et al. 2016; Thokchom and Yadava 2017). Bamboo harvesting does not remove the entire plant, therefore, preventing the release of CO_2 at post-harvest period (Nath et al. 2015a, b). Also, appropriately managed and regularly harvested bamboo can sequester more carbon than bamboo in natural state (Wang et al. 2013; Thokchom and Yadava 2017; Nath et al. 2018).

Likewise, since bamboo forests are an integral component of most of the tropical forest ecosystems and adaptive to adverse site conditions, they can be planted in degraded tropical forests (Sohel et al. 2015; Ling et al. 2016; Qin et al. 2017). They can be grown on marginal land and regenerate annually through an extensive rhizome system, and they lend themselves to soil stabilization, reducing erosion, increasing slope stability, and contributing significantly to the restoration of degraded lands, which are essential to combat desertification (Zhou et al. 2011; Ling et al. 2016).

Owing to their natural resilience, bamboos increase farmers' resilience against climate change, protect livelihood options, and provide them the opportunity for sustainable use of these resources (Lobovikov et al. 2007; INBAR 2010a; Thokchom and Yadava 2017; Nath et al. 2018). Bamboos can grow outside forests as agroforestry systems on agricultural lands and farms, in the rural landscape, and along roads, rivers, and human settlements and trees in and around cities (FAO 2010a, b). While contributing to environmental sustainability, they also provide income as well as a range of goods and ecosystem services for rural households, thus, contributing to food security and poverty eradication.

Bamboos provide a wide range of socioeconomic benefits, such as housing and construction material, material for handicraft and tools, animal fodder, medicine, irrigation pipes and channels, fuelwood, and fiber for fabrics (Lalhruaitluanga and Prasad 2009; INBAR 2010b; Lobovikov et al. 2012; Hogarth and Belcher 2013; Rodriguez et al. 2014; Phimmachanh et al. 2015). Due to its high utility, which is closely interwoven with the life of the people, it is known as the "poor man's timber," "green gold of the forest," and "friend of the people" (Handique et al.

2010; Kithan 2014; Gupta and Ranjan 2016). By and large, bamboos have enormous potential to improve socioeconomic life of people, alleviating environmental problems and establishing sustainable development (Zhou et al. 2005; Lobovikov et al. 2012; Clara et al. 2017).

16.2 Bamboo-Based Agroforestry: Diversity, Function, and Its Role in Socio-economy

Agroforestry is the collective term for land-use systems and technologies in which woody perennials (e.g., trees, shrubs, palms, or bamboos) and agricultural crops or animals are used deliberately on the same parcel of land in some form of spatial and temporal arrangement (Wood 1990; Nair 1992). In simple definition, agroforestry is the production of trees and of non-tree crops or animals on the same piece of land (Igbokwe et al. 2016). It can also be defined as a system of land management that integrates tree and shrub plantings with crops or livestock in order to generate economic, environmental, and social benefits (Nath et al. 2009; Rancāne et al. 2014).

The concept of agroforestry stems from the expected role of on-farm and off-farm tree production in supporting sustainable land use and natural resource management (Nair et al. 2009). The rationale behind the development of this system is both ecological and economical between the trees and other components interacting in the system (FAO 2010a, b; Shapiro and Frank 2016). However, these age-old practices of growing crops and trees together were bypassed in the development of modern agriculture and forestry, which focused on obtaining optimum yield through growing trees and crops in monocultural production systems (Tangjang and Nair 2016). Moreover, agriculture and forestry were often treated separately although these two sectors are usually interwoven on the landscape and share many common goals (Partey et al. 2017).

Recently, realizing the adverse ecological and social consequences of input-intensive monocultural production systems and traditional and age-old practices of growing trees and crops together on the same unit of land has got attention (Nair et al. 2009). Consequently, agroforestry is recognized as an integrated applied science that has the potential for addressing many of the land management and environmental problems found in both developing and industrialized nations (Nair et al. 2009; Akoto et al. 2018). Hence, a large number of traditional or indigenous as well as improved or modern agroforestry systems have been recognized in different parts of the world (Partey et al. 2017).

16.2.1 Diversity of Bamboo-Based Agroforestry

Bamboo-based agroforestry can play an important role in enhancing productivity, sustainability, and resource conservation of developing countries in the tropics (Kittur et al. 2016). Many of the useful bamboo species can occupy the same ecological niche as trees and are well suited for agroforestry (Jha and Lalnunmawia

2004). Bamboo has many advantages over trees such as relatively short time span from planting to harvest versatility of use which outmatches most tree species and the ability to provide building materials and edible products for many years or even decades (Tewari et al. 2015). They reach structural maturity within 3 years and the mean annual increment of medium to large size faster than many other fast-growing tree species (Zhou et al. 2011).

Bamboos generate plenty of oxygen and low light intensity, protect against ultraviolet rays, and sequester more carbon than fast-growing tropical and subtropical trees, and are thus, considered as atmospheric purifiers (Banerjee et al. 2009). Furthermore, they are peerless erosion control agents, and their netlike root system creates an effective mechanism for watershed protection, stitching the soil together along fragile riverbanks and deforested areas and in areas prone to earthquakes and mud slides (Tewari et al. 2015). Bamboos are adaptive to adverse site conditions and can be planted in degraded tropical forests (Sohel et al. 2015; Qin et al. 2017). Thus, in the face of global climate change, deep-rooted poverty, fast degradation of land resources, and other environmental hazards, bamboo-based agroforestry is indeed a viable option for enhancing productivity, resource conservation, and sustainability.

As literature sources indicate (Viswanath et al. 2007; Nath and Das 2008; Banerjee et al. 2009; Kittur et al. 2016; Tangjang and Nair 2016), bamboo-based agroforestry has been widely practiced in Asia continent than other bamboo-growing parts of the world. Bamboo-based agroforestry systems have been integrated on farmlands, homesteads, degraded lands, and riparian filter (Tewari et al. 2015). There have been reports on the attempts to cultivate agricultural crops in bamboo plantations. As Mailly et al. (1997) noted, the integration of bamboo on croplands is confirmed a suitable approach for increased productivity of food crops and non-food biomass in many parts of Asia. The agrisilviculture, silvipastoral, agri-silvipastoral, and agri-silvihorticultural system and bamboo in home gardens are some of the agroforestry models in which bamboos are grown (Nath and Das 2008; Banerjee et al. 2009; Tewari et al. 2015).

Nath and Das (2008) found that bamboo forms an important component in the traditional agroforestry system of Assam region, Northeast India. The study reported that bamboos in the agroforestry system are grown in the home gardens and in the form of grove where bamboo is grown in pure or mixed with other vegetation. Similar studies conducted by Banik (2016) showed that *Bambusa balcooa* [Roxb.], *B. bambos* [L. Voss], *B. nutans* [Ex. Munro], *B. tulda* [Roxb.], and *B. vulgaris* var. *vittata* [Riviere and C. Riviere] are common bamboos species in the homestead of moist humid zones of Northeast India, West Bengal and Odisha, whereas, *B. vulgaris* and *B. nutans* grow on homesteads throughout Bangladesh.

As noted by Tewari et al. (2015), in Tarai region of Uttarakhand, *B. balcooa*, *B. nutans*, *B. tulda*, and *D. hamiltonii* with *bael* [*Aegle marmelos*], citrus [*Citrus aurantifolia*], *kathal* [*Artocarpus heterophyllus*], moringa [*Moringa oleifera*], neem [*Azadirachta indica*], and semul [*Bombax ceiba*] are cultivated by Bengali migrants in their homesteads. They also reported that bamboos are grown in combination with crops, such as *siris* [*Albizia lebbeck*], *aonla* [*Emblica officinalis*], *bakain* [*Melia* *azedarach*], banana [*Musa*], betel nut [*Areca catechu*], coconut [*Cocos nucifera*], neem [*Azadirachta indica*], and semul [*Bombax ceiba*] in the region.

In degraded land of Mizoram, intercropping of soya bean with *Melocanna baccifera* and *D. longispathus* is feasible and gave better results than pure bamboo stands (Jha et al. 2004). They reported that the bamboo species are also intercropped with maize and peanut in Thailand. Banik (2016) articulated that seedlings of *B. bambos*, *B. nutans*, and *D. strictus* are successfully intercropped with either maize or soya bean in Jabalpur, Madhya Pradesh. Similarly, intercropping studies were conducted in Raipur (Chhattisgarh), with *B. bambos* and *D. strictus* (Naugrayia 2014). In India, Kharif rice, soya bean, wheat, mustard, and linseed crops were grown at 8 × 3 m spacing in 2009–2010 and at 8 × 6 m in 2010–2011 and 2011–2012. Spice crop of turmeric was also taken on the bunds between the bamboo clumps. In similar environment, the production of fodder crop under bamboo-based silvipastoral system (at 10 × 5 m spacing) was found maximum with *B. nutans* (13.46 Mg ha^{-1}) followed by *B. vulgaris* (12.61 Mg ha^{-1}) and minimum under *B. bambos* (9.37 Mg ha^{-1}) for the third year (Naugrayia 2014). Similarly, bamboo-based agroforestry systems constituted a sustainable land-use option for the Dong Cao Catchment in northern Vietnam where bamboo, *Acacia mangium*, and *Tephrosia candida* were chosen as test species for simulating and comparing filter effects of different agroforestry systems with intercropping, hedgegrows, or fallow rotation (Nguyen 2004).

Furthermore, a bamboo-based agroforestry system, involving two bamboo species (*B. balcooa* and *B. tulda*) in red and laterite zone of West Bengal, was studied by Banerjee et al. (2009). The study results revealed that agricultural crops like paddy, groundnut, cowpea, lady's finger, bottle gourd, pigeon pea, turmeric, elephant foot yam, and colocasia have immense potentiality of providing livelihood security to the poor farmers through self-employment and higher income. Likewise, Kittur et al. (2016) examined the performance of turmeric as an understory crop in 7-year-old bamboo [*Dendrocalamus strictus* (Roxb.) Nees)] stands of varying spacing treatments (4 × 4, 6 × 6, 8 × 8, 10 × 10, and 12 × 12 m) in Kerala, India. Results showed that bamboo roots compete with understory crop at 4 × 4 m up to 8 × 8 m spacing; beyond 8 × 8 m spacing, however, there were only marginal competitive interactions. For optimal performance of the understory turmeric in mixed species systems, the study recommended wider bamboo spacings beyond 8 × 8 m. While cultivated in mixed cropping home gardens in Kerala, bamboo (*B. bambos*) holds the second position in terms of profitability among the crop groups (Krishnankutty 2004).

Integrated bamboo and pine agroforestry in Ziro Valley of India has been an integral part of the local system, which is judiciously guarded and meticulously tended by all community members as it fulfills various basic rural needs (Tangjang and Nair 2016). Likewise, bamboos could be planted as windbreaks on the boundaries of agricultural fields and orchards for protecting them from high-speed wind. For example, in Anji, Zhejiang Province of eastern China, *moso* bamboo plantations flourish alongside rice fields (Pérez et al. 2001). Bamboos were planted on the borders of agricultural fields and orchards for protecting crops from high-speed wind in Nepal (Banik et al. 2008). In Sikkim region, farmers planted *D. hamiltonii* and *D. sikkimensis* in agricultural fields along the irrigation channels and stream banks to meet the fodder needs of their livestock, while *B. arundinacea* grew in depressed and water-logged sites in Andhra Pradesh (Jha and Lalnunmawia 2004).

By and large, from Asian experience, it is possible to conclude that bamboo-based agroforestry is a promising land-use option for enhancing productivity, rising socioeconomic benefits, and sustainable land management in tropical bamboo-producing countries. Currently, agroforestry innovations are recognized and encouraged as sustainable approaches to ensure food security and achieve the UN SDGs. By enhancing livelihood security and quality of life, conserving ecosystems, and fostering economic growth, the bamboo-based agroforestry systems could pave a way for achieving sustainable development. However, the socioeconomic and ecological importance of bamboo is not far-fetched yet, particularly with the provision of huge biomass source for renewable energy, potential for restoring degraded forestlands and as a sustainable carbon sink. Therefore, it is possible to optimize its functionality by incorporating bamboo into mixed-use agroforestry complexes.

16.2.2 Socioeconomic Roles of Bamboo-Based Agroforestry Systems

Agroforestry systems developed over the years by innovative efforts involve growing bamboo on their fields (Sumpam and Nair 2016). Thus, agroforestry is of great importance in recent times, primarily because of meeting the diversified needs of people and for sustaining the frazzle ecosystem for generations to come (Bhabesh 2015). In agroforestry systems, the bamboos play important role in the livelihoods of rural people by providing employment, energy, nutritious foods, and a wide range of goods and also balancing ecosystems. Bamboo-based agroforestry system is currently being promoted as a viable land-use option to reduce dependence on natural forest for wood, fuelwood, and construction materials. Bamboos have enormous economic applications; hence, people call them "green gold," "poor man's timber," "bamboo, friend of the people," and "cradle to coffin timber" (Seethalakshmi and Kumar 1998; Tewari et al. 2015; Akwada and Akinlabi 2016) due to their vital role in improving the socioeconomic status of rural populations (Asha et al. 2018). Therefore, bamboo-based agroforestry systems are one of the important components to improve socioeconomic status of people as well as conservation and sustainability of the environment (Diwakar et al. 2018).

16.2.2.1 Social Roles of Bamboo-Based Agroforestry Systems

Agroforestry systems provide numerous economic, social, recreational, and environmental benefits (Tengnas 1994; Leakey 1998; Unofia et al. 2012) owing to the variety of composition in the system that diversifies the income options. Incorporation of bamboos in the farmland or bamboo-based agroforestry is a very important practice that is a highly relevant livelihood option for local farmers. Humans depend on forests and forest products for the need and satisfaction of

Table 16.1 Sociocultural benefits of bamboo products

Types (parts)	Uses	Sources
Bamboo shoots	Health food (high proteins, amino acids, carbohydrates, many important minerals, and vitamins) and make up for dietary deficiencies of nutrients in the diet	Liu et al. (2016), Thakur et al. (2016), Devi (2013), Nirmala et al. (2011), Anusriti et al. (2017)
Bamboo fibers	Common ingredient in breakfast cereals, fruit juices, bakery and meat products, sauces, shredded cheeses, cookies, pastas, snacks, frozen desserts	Chongtham et al. (2011), Felisberto et al. (2017)
Value-added products and traditional drinks and medicine	Bamboo shoots are consumed in raw, canned, boiled, marinated, fermented, frozen, liquid, and medicinal forms for food, medicine, and both traditional and modern drinks	Choudhury et al. (2011), Thakur et al. (2016), Satya et al. (2010), Shukla et al. (2012), Karanja et al. (2015)
Construction materials and home appliance	Cost effective, easy to bend and lithe, easy availability, process ability	Patil and Mutkekar (2014), Nurdiah (2016), Boran et al. (2013), Nwoke and Ugwuishiwu (2011)
Enterprises and employment	Employment generation and sustainable livelihoods in rural communities	Swamy (2011), Alamgir (2007)
Bamboo fiber and starchy pulp	For clothing and cellulose fiber for pulp	Saravanan and Prakash (2007), Sowmya et al. (2016)

cultures, knowledge systems, religions, social interactions, and amenity services. Bamboos are among the forest products mainly categorized as non-timber forest products (Lay et al. 1996), which have been getting attention of scientists and practitioners to be used or incorporated in the agroforestry systems.

The social functions of forests and forest products are often more difficult to measure and can vary considerably among countries, depending on their level of development and traditions (FAO 2005). However, the monetarily immeasurable social values are very important for the livelihoods of humans. For instance, the significant non-commercial benefits, including wildlife, recreation, aesthetics, and wilderness values, are known by their indirect support for the life of human beings in the key aspects of social equity. Therefore, subsistence benefits from bamboo-based agroforestry systems, including social values or the number of people employed and earning incomes, may be a better indication of their social values.

Since time immemorial, bamboos play a significant role in human civilization and are contributing to the subsistence of people living in the tropical and subtropical belts in Asia, Latin America, and Africa (Devi 2013). As can be seen in Table 16.1, bamboo provides a wide range of benefits and can be used in different ways as food, medicine, drinks, side dishes, clothes, and sources of construction materials. Also, the utilization pattern of bamboo shoots in most of the countries indicates that it can be consumed in various ways as raw, canned, dried, boiled, and fermented or medicinal (Basumatary et al. 2017).

Bamboos are the most important non-timber forest products, providing food, raw materials, and shelters for a good part of the world's population (FAO 2007; Sudhir 2014). For instance, the shoots of these plants are regarded as vegetable in East and Southeast Asian nations (Fidel et al. 2014). Apart from being delicious, research results are confirming that bamboo shoots are also rich in minerals and nutrient components, such as carbohydrates, proteins, as well as fiber, and are low in fat and sugar, which could be helpful in mitigating the problem of malnutrition (Nirmala et al. 2011; Nongdam and Leimapokpam 2014; Anusriti et al. 2017). Thus, "bamboo" is mostly considered as a "versatile and poor man tree" because it is readily available for poor people at often very low costs in a short period, mostly in many developing countries where it is available (Akwada and Akinlabi 2016).

Agroforestry can be used to diversify and intensify farming systems through the integration of indigenous trees producing marketable timber and non-timber forest products. It is described in terms of an agroecological succession, in which climax agroforests are biodiverse, highly productive, and profitable (Leaky 1999). In this regard, the inclusion of bamboos, multifunctional plants, in the agroforestry system got more attention of farmers due to their fast growth and straightness, combined with short period in which they attain maturity, and the multi-functioning property. Hence, the traditional uses of bamboo, including edible bamboo shoots and bamboo shade for houses and household farm utilities, are acknowledged by rural people in supporting their livelihood.

16.2.2.2 Economic Roles of Bamboo-Based Agroforestry System

Trees are important components of agricultural landscapes where they provide a range of ecosystem services that support livelihoods and maintain the productivity of agricultural land through litterfall, decay of fine roots, protection of erosive agents, and maintenance of the soil moisture. The production of sufficient food for an increasing global population while conserving natural capital is a major challenge to humanity (Edmundo et al. 2018). In Asia, the integration of bamboo within agricultural systems is confirmed as a suitable approach for increased productivity of food crops and non-food biomass (Mailly et al. 1997). In sub-Saharan Africa, agroforestry system and integration of bamboos in the agricultural land contributed to poverty reduction and improved livelihoods in the region (Samuel et al. 2017). Bamboos in China have restored fragile ecosystems, provided benefits to local communities, alleviated rural poverty, and eased timber shortages (Guangyu et al. 2008).

Agroforestry with bamboos has considerable potential for providing food and nutritional security and for contributing to economic development of developing countries (Kittur et al. 2016). This is because bamboo is an extremely versatile plant capable of providing ecological, economic, and livelihood security to the people (Banerjee et al. 2009). As agroforestry is a dynamic eco-friendly natural resources management system, integration of bamboos in farms and in the agricultural landscapes diversifies and sustains production for increased economic benefits for land users at all levels.

Agroforestry has both productive and protective or service functions. In this regard, bamboo-based agroforestry system plays a great role in providing forest products, including fuelwood, fodder, fruits, and shoots, with construction wood products. Different studies revealed that economic return from bamboo as a non-timber forest product and integration of bamboo in farm as agroforestry system is high (Khilesh 2012; Hassnain et al. 2013; Solomon et al. 2014; Nwaihu et al. 2015). Similarly, the comparative studies conducted on bamboo-based agroforestry and sole crop lands found that the bamboo-based agroforestry system has higher monetary return than sole crop agricultural production system (Mcneely and Schroth 2006; Rahangdale et al. 2014; Pooja et al. 2017). In India, incorporation of bamboo in cropland resulted in higher production than mono-cropping system of agricultural production (Rajesh et al. 2014). Similarly, in China, *moso* bamboo (*Phyllostachys heterocycla* var. *pubescens* or *P. edulis*) or "MaoZhu" is the third most important plant species for timber production next to *Pinus massoniana* and *Cunninghamia lanceolata* (Chinese Fir) (Fidel et al. 2014).

Generally, bamboo, as a traded commodity, has excellent potential to contribute to inclusive development and foreign trade balance (Rajesh et al. 2014). Thus, bamboo-based agroforestry has a promising future as a part of the solution to the twenty-first-century poverty eradication and livelihood improvement challenges.

16.3 Bamboo-Based Agroforestry: Soil Health Management

Forest and land degradation are serious global problems, particularly in developing countries. According to FAO (2011), approximately one billion people or 15% of the world population live in degraded areas, and one third of the world's population is considered to be affected by land degradation. Here the term land degradation is defined as a persistent decline in the provision of goods and services that an ecosystem provides, including biological and water-related goods and services as well as land-related social and economic goods and services (FAO 2011), whereas forest degradation is referred to as a loss of forest structure, productivity, and native species diversity (Lamb and Gilmour 2003). It is a reduction in the capacity of forests to provide goods and services.

To date, around 47% of the world's potential forest area has been cleared or degraded to make ways for crops, cattle, cities, and roads (Buckingham 2014). The continuous forest and land degradation have posed an adverse impact on the environment, including disruption of ecosystem services, soil quality degradation, loss of water quality, and threatening biodiversity (FAO 2015). This in turn adversely affected and continues to affect the livelihoods; well-being; food, water, and energy security; and resilience (defined as the ability of people to adapt to climate change) of millions of people (Liniger et al. 2011). Reversing forest and land degradation is, therefore, an imperative task for humankind.

The restoration of degraded lands through landscape approach is a valuable tool for enhancing livelihoods and sustainability of land resources (Hillbrand et al. 2017). From this perspective, Lamb and Gilmour (2003) defined forest and landscape restoration as a process that aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes. According to the Global Partnership on Forest and Landscape Restoration (GPFLR 2017), the area of land potentially available for landscape restoration has been estimated at 2.2 billion ha. Of this, 1.5 billion ha is best suited to mosaic restoration, where forests and trees are combined with other land uses, such as agroforestry (Rebelo and Buckingham 2015). For restoring degraded forests and agricultural lands, agroforestry has some peculiar advantages, especially in landscapes where land for food production is limited and human populations are large or increasing (Lamb and Gilmour 2003).

As biological approach is effective and most economical in the restoration of degraded lands (Mishra et al. 2014), there is an axiomatic need to introduce fast-growing bamboo plants in degraded areas (Musau 2016). Bamboos are an integral component of most of the tropical forest ecosystems and adaptive to adverse site conditions, so that they can be planted in the degraded tropical forests (Qin et al. 2017). The bamboos can be grown on poor soils of marginal land and regenerate annually through an extensive root system and lend themselves to soil stabilization, reducing erosion, increasing slope stability, and contributing significantly to the restoration of degraded lands, which are essential to combat desertification (Zhou et al. 2011; Ling et al. 2016).

Adaptive capability and nutrient and water conservation potential of bamboos enable them as forerunner plants in the eco-restoration of degraded lands (Mishra et al. 2014). Because of the fast-growing nature and the dense foliage of bamboos, they are able to maintain the thick layer of litter (INBAR 2010a). This litter layer maintains microclimate in the understory and soil moisture, the most important factors for the restoration of degraded lands (Sharma et al. 2018). Therefore, by planting bamboo in degraded parts of landscapes, degraded lands can be restored to productive use; thereby pressures on remaining forests will be abated (Buckingham 2014). Furthermore, bamboo diversifies the landscapes, providing food and habitat for numerous species of insects, birds, and animals (FAO and INBAR 2018).

According to FAO and INBAR (2018), recently, an increasing number of countries have begun to identify and explicitly include bamboo as high-priority species for use in landscape restoration. Cameroon, China, Ethiopia, Kenya, Ghana, India, Madagascar, the Philippines, and Vietnam are some of the countries that include bamboo in their sustainable land management programs. Likewise, most member countries of INBAR are promoting the use of bamboo for land restoration as part of the Bonn Challenge (Sharma et al. 2018). Despite case studies of bamboo restoration remain relatively small scale, some have shown promises (Rebelo and Buckingham 2015; Sharma et al. 2018). For example, in Africa, the Organization of African Bamboo is preparing nurseries for large-scale restoration of degraded land with bamboo (Partey et al. 2017). The EcoPlanet Bamboo has been active in Nicaragua, restoring 5000 ha of degraded pastureland in Latin America (Eco Planet Bamboo 2014). Likewise, in India, the INBAR completed a prize-winning bamboo restoration project which turned a degraded mining area into a green and productive land (Benton 2014).

The Eco Planet Bamboo project was launched at Nicaragua in 2011. The project used *Guadua aculeata*, a native species of giant clumping bamboo that occurs naturally within the forest, to restore 6500 ha of highly degraded land into commercial plantations and provide more than 250 permanent jobs. An additional 600 ha of remnant patches of tropical forest has been conserved, resulting in habitat connectivity and a more diverse ecosystem, while 1000 ha is undergoing restoration (Eco Planet Bamboo 2014). Similarly, the organization employed a different model in South Africa's Eastern Cape in 2012. There, the restoration of 480 ha of land that was depleted by over a century of chemically intensive pineapple farming focused on the regeneration of exhausted agricultural soils. The project also stimulated local economies by providing an alternative fiber for international carbon and charcoal markets (Eco Planet Bamboo 2015).

Furthermore, in India, the study conducted by FAO and INBAR (2018) shows how a degraded mining area exhibited a remarkable recovery after planting bamboos. The study reported that agricultural crops and tree species had been incorporated into a bamboo landscape, and within 20 years, the groundwater table had increased by 10 m. As a result of its success, the project was scaled up to cover 100,000 ha of degraded land in 600 villages and for the economic and social benefit of over one million people. Similarly, in Colombia, planting bamboo in degraded soil improved soil quality, decreasing soil compaction by more than half. In Nepal, a similar plantation helped reduce soil erosion and flood damage (FAO and INBAR 2018). As Sharma et al. (2018) noted, recently countries like China, India, and the Philippines have incorporated bamboo in their national restoration plans. For example, the Chinese State Forest Administration has planned to restore three million ha, the Philippines aims to restore 500,000 ha, and India too has programmed to restore 100,000 ha of degraded landscape using bamboos.

By and large, the use of diverse tree species and other practices employed in agroforestry systems can represent alternative forms of increasing soil fertility and maintaining agricultural production, with important practical applications for the sustainability of tropical agriculture (Pinho et al. 2012).

16.4 Bamboo-Based Agroforestry: Climate Change Adaptation and Mitigation

In today's world, climate change is generally recognized as one of the greatest challenges for humankind. The challenges after Copenhagen will be to put into practice whatever is agreed and to develop the approaches, policies, and practices needed to effectively integrate the objectives of climate change mitigation and adaptation with sustainable forest management (SFM) and biodiversity protection (Bodegom et al. 2009). Forest ecosystems capture and store carbon dioxide, making a major contribution to the mitigation of climate change. In this regard, the bamboo forests are invaluable plant species for adapting and mitigating climate change.

Bamboos, which are characterized by a complex network of rhizome-root system (Lobovikov et al. 2009; INBAR 2010a), can sequester more carbon than fast-growing tropical and subtropical trees under comparable conditions (Lobovikov et al. 2012; Li et al. 2016; Thokchom and Yadava 2017). Bamboo harvesting does not remove the entire plant, therefore, preventing the release of CO_2 at post-harvest period (Nath et al. 2015a, b; Ling et al. 2016). Consequently, to date, bamboo is widely regarded as an ideal plant to sequester carbon and expected to play a bigger role in mitigating the impact of future climate change (Song et al. 2011).

The International Network of Bamboo and Rattan (INBAR) had shown the roles that bamboo plays in fighting climate change in different ways. It combats climate change by sequestering carbon in its biomass, reducing carbon release by offering alternative highly renewable sources of biomass energy. Adaptation by the rapid establishment and growth of bamboos reduces the exposure to disaster, and it restores the degraded lands with friendly property to the soils and livelihood diversification. Bamboo's fast growth, ability to grow on varied soils and climate, renewability, and positive socioeconomic impacts make them an excellent species for combating climate change (Mohit and Neelu 2012).

Bamboo's carbon sequestration rate can equal or surpasses that of fast-growth trees over short time periods in a new plantation, but only when bamboo is properly harvested and managed (Yiping et al. 2010). Studies have shown that appropriately managed and regularly harvested bamboo can sequester more carbon than bamboo in natural state (Thokchom and Yadava 2015). Because, cost-effective managed ecosystems that can substantially remove atmospheric CO_2 while providing essential societal benefits are important (Nath et al. 2015a, b). A study by Yuen et al. (2017) reported the comparative study results about the importance of bamboos with other tree species on the carbon sink, mitigating the effect of climate change, and its ability to provide key ecosystem services for humans including stabilizing hillslopes from accelerated soil erosion, improving soil fertility, and providing food and construction materials. According to carbon density of bamboo forest ecosystems in China, the estimated global bamboo carbon stock is about 4 Pg (1 Pg = 1015 g; 1 Tg = 1012 g; 1 ton = 106 g), accounting for 0.43–0.61% of total global forest carbon stock (Mei 2017).

Bamboo helps us all mitigate and adapt the effects of climate change by absorbing and storing carbon; protecting forests and watersheds; insulating environments against extreme weather; providing low-cost greenhousing and infrastructure; providing cleaner biofuels; and providing renewable, sustainable resources for generating incomes (Thibbotuwawa 2019). Thus, the innovative use of bamboo by incorporating in the form of agroforestry in climate smart agriculture could give a multifaceted benefit. Therefore, the enhanced protection and management of natural ecosystems and more sustainable management of natural resources and agricultural crops can play a critical role in climate change adaptation strategies (INBAR 2010a, b; World Bank 2010).

16.5 Management Options and Strategies for Promotion of Bamboo-Based Agroforestry

More than any other plant on earth, bamboo has a great variety of uses to people and their environment (Rabik and Brown 2003). Bamboo has a considerable importance for both ecology and society, especially for rural society (Utami et al. 2018). Hence, to get the sustainable benefit from the bamboo resources, sustainable management is very important as the cost of management can be recovered rapidly as bamboo grows fast and productive stands are established within 3–4 years (INBAR 2003). However, one of the major causes of the low productivity in the bamboo plantation is poor management of the stand. Regular management activities including weeding, regulating composition, removal of climbers and dried leaves, and mounding before rainy season of each year around the clump are helpful to facilitate growth and enhance the productivity. For instance, the understanding of planting spacing and root activity are important for the growth and productivity of bamboo in the agroforestry system as spacing treatments exerted profound influence on bamboo growth (Kittur et al. 2016).

Bamboo grows much faster than timber tree species; it requires less intensive management and expertise. When the young forest begins to produce shoots in large numbers, it has reached its adult stage. Measures to achieve high yields as the forest becomes mature mainly consist of improving growing conditions for the forest and managing its population structure (Troya and Xu 2014). Lack of silvicultural intervention in the bamboo results in the profuse uniformly dense mat of regeneration preventing the formation of bamboo clumps (Chaubey et al. 2013). Also, competition between grass weeds and bamboo results in poor performance (Mulatu et al. 2016).

To get the planting materials, adopting the regeneration seedlings by maintaining spacing of 4 m $\times$ 4 m is better for proper growth of bamboo seedlings (Mulatu et al. 2016). The use of seeds, seedlings, or juvenile plant stock as well as mature clumps is another source of plant propagation (Banik 1994). For the success of bamboo-based agroforestry, there has to be a known source of seedlings for planting, and one of the sources for the seedling could be bamboo flowering. However, observation of the flowering phenomena of bamboo is very complicated as most of bamboo species seldom flower even if they are hundred years old (Zhu et al. 1994). Due to gregarious flowering, it is estimated that more than ten million tons of bamboo would be available in accessible area that would need immediate attention, so planning for timely harvest and utilization are utmost importance (Tripathi et al. 2002).

Worldwide, approximately more than 2.5 billion people trade in or use bamboo (Puran et al. 2018). Bamboo-based agroforestry is currently being promoted as a viable option for social, economic, and environmental benefits. Well-managed bamboo in agroforestry has tremendous potential to contribute to sustainable development and to a greater economy. Despite its significant contribution to the economy, society, and environment, the bamboo industry in some parts of the world remains underdeveloped. Thus, promotion of bamboo-based agroforestry is important to enhance the benefit from the resources in a better way to fulfill diverse socioeconomic needs of the societies and other numerous environmental services. For the easy promotion and expansion and incorporation of bamboo in the agroforestry systems, aligning the design and introduction of bamboo-based agroforestry to the needs of farmers, information on the determinants of bamboo acceptability and adoption is necessary (Akoto et al. 2018).

The bamboo plantation will be managed effectively if the harvesting is regulated on a sustainable yield basis. Although bamboo is a renewable resource, the capacity of this plant to regenerate is hindered by indiscriminate and destructive harvesting methods (UNIDO 2009). A study by Darabant et al. (2016) confirmed that the total number of culms positively influenced the number of shoots regenerated, and a much stronger relationship was detected between the number of culms harvested and number of shoots regenerated. To achieve its sustainability, harvesting of the bamboo should be done selectively. Hence, only mature culms which are 3–4 years should be harvested, and removing the entire culms is not recommended unless it has been seriously infected by a disease (UNIDO 2009). Additionally, felling of bamboo ought to be avoided in the wet and moist seasons as the young shoots are still in the process of growing (Sulthoni 1996); thus, harvesting should be done in the dry seasons.

16.6 Conclusions

Bamboos are gaining increased attention as agroforestry trees and an alternative crop with multiple uses and benefits. Beside to their multiple uses, the properties of these long-lived, woody stemmed perennial grasses made them special to be incorporated in the different agroforestry systems in the farmlands. Bamboo-based agroforestry systems are important for immeasurable social values, economic diversification, income development, management and maintenance of soil properties, lowering of light intensity, and protection against UV radiations and as atmospheric and soil purifier.

Many of the most useful bamboo species can occupy much the same ecological niche as trees and are well suited for agroforestry. There are various species of bamboo in the world, especially in subtropical and tropical regions in developing countries, used for agroforestry.

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Part III

Synthesis

Agroforestry Developments for Degraded Landscapes: A Synthesis

17

Jagdish Chander Dagar and Sharda Rani Gupta

Abstract

Due to many natural and anthropogenic factors, about two billion hectares of land is degraded globally. To meet the demands of ever-increasing population, every inch of degraded land is to be brought under cultivation. Agroforestry is an adjunct of sustainable agriculture since its evolution as science. In modern scenario of climate change, it is being considered a problem-solving science. The social, economic, and environmental costs are high for the on- and off-farm reclamation techniques, and agroforestry is now emerging as a potential tool not only for arresting land degradation but also for providing other environmental services like adaptation to climate change, sequestration of carbon, and biodiversity conservation. Recent research and developmental efforts, though experimentally in small plots or under microsite conditions in catchments, have demonstrated that trees can be successfully established through appropriate site preparation, careful species selection, and post-planting care. There is need for the collaboration between scientists, farmers, and land managers for the large-scale promotion of agroforestry on degraded lands with due consideration to the insurance, legal, and institutional arrangements by the implementing agencies. During last four decades, agroforestry as a science has gained global attention as a multi-disciplinary science playing important role in sustainable food production, meeting nutrient requirements of rural population, rehabilitation of degraded landscapes, improving biodiversity, and mitigating climate change. Recent research developments in agroforestry for degraded landscapes in tropical, subtropical, and temperate regions have been synthesized in this concluding chapter.

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Synthesis of results · Advances in agroforestry · Degraded landscapes · Mitigating climate change · Livelihood security · Environmental services · Policy issues

17.1 Introduction

Land degradation is threatening food security as well as ecosystem goods and services and depleting ecosystems in different regions of the world. About two billion ha of land in the world is affected by various forms of natural and anthropogenic land degradation. The main causes of land degradation are inappropriate land use and management, over-exploitation of natural resources, loss of soil organic carbon, soil erosion, salinization, acidification, waterlogging, desertification, mining, soil compaction, nutrient imbalance, and loss of soil biodiversity. Besides meeting food and other needs of ever-increasing population, ecological restoration of degraded ecosystems and landscapes is a global priority. Agroforestry encompasses a wide range of approaches and technologies for restoring degraded lands for production of agricultural commodities and improving environmental services. Four decades of agroforestry research and development, as reviewed in this book, indicate that agroforestry has evolved as a problem-solving science primarily, as a means for sustaining agricultural productivity in marginal lands and alleviating many of the problems of land and environmental degradation. Agroforestry technologies have been applied to rehabilitate or restore degraded lands due to soil erosion, deforestation, rangeland degradation, salinization, waterlogging, acidification, mining sites, and over-extraction at various scales, from plot- to farm-levels to large agricultural and farming enterprises. Most of the agroforestry research has focused on biophysical parameters at the farm level. Landscape-level research undertakings are few because of the complexity of landscape, the long-time series of data needed to study economic and social impacts, and the lack of baseline studies on levels larger than the farm. These concerns are expressed by the research results presented in various chapters in this book, using different models of agroforestry under specific environmental conditions. Therefore, a quick review of chapters and critical synthesis of the results obtained in different studies from both tropical and temperate regions will be pertinent for a broader understanding of the state of existing knowledge, and the future research needs to develop agroforestry on degraded lands for environmental and livelihood security.

17.2 Synthesis

In modern times virtually all global land resources are afflicted by degradation processes to some degree. As a consequence of ever-increasing human population and thus, over-exploitation of natural resources through deforestation, over-grazing, and mismanagement of land and water resources to meet the demands of food and other commodities, particularly in developing countries (mainly in Asia and Africa), the situation has become alarming. Since 1990s, a notable development has taken place in the field of agroforestry, and its recognition among different stakeholders as sustainable agriculture has gained importance. However, the relevance of agroforestry technologies as a practicable tool for restoring degraded landscapes and as a problem-solving science has gained momentum during last four decades. In this compilation in two volumes, a detailed account of the global extent of land degradation; physical, chemical, and biological processes of land degradation; ecological restoration at the ecosystem and landscape level; and the potential of agroforestry systems to enhance biodiversity conservation, livelihood security, and mitigating climate change have been discussed.

During the last four decades of research on agroforestry systems in tropical drylands, substantial information has been generated and compiled recognizing the potentials of agroforestry to enhance livelihood security in Africa and Indian subcontinent. Some useful trees such as *Faidherbia albida*, *Prosopis africana*, and *Prosopis cineraria* have been identified to grow with field crops in rain-fed ecologies. These tree species do not have any negative impact on crop yields; rather they enhance the productivity of the system, increase soil organic carbon, and enrich nitrogen contents besides providing nutrient-rich fodder for animals. Many fertilizer trees and shrubs are explored for moisture-stressed conditions. Species such as *Prosopis africana*, *Vitellaria paradoxa*, *F. albida*, *Acacia senegal*, *A. laeta*, and *Parkia biglobosa* are recognized for parklands of Sudan and other dry regions in Africa, where gum is collected from these trees and *F. albida* is intercropped successfully with maize. Some of these trees and shrubs such as *Balanites aegyptiaca*, *Acacia raddiana*, *F. albida*, *Combretum aculeatum*, *Boscia angustifolia*, and *Maerua crassifolia* are rich in crude protein and grown as fodder banks. The indigenous fruit trees such as marula (*Sclerocarya birrea*) from Southern Africa, in dry West Africa, and *Emblica officinalis*, *Carissa carandas*, *Ziziphus mauritiana*, *Z. nummularia*, and *Aegle marmelos*, for the Indian subcontinent, have been advocated for domestication in different regions. There is extensive information concerning the potential uses of forest and fruit trees, but little effort has been made to improve these trees, techniques of multiplication for quality germplasm to be made available to farmers; value addition; establishment of small industries in rural areas to add values to farm produce for income generation; and to train the stakeholders and implementing the results on farmers' fields.

Kemeuze et al. (Chap. 6, Vol 1) have analyzed land-use management by smallholders' households in dry landscapes in the semiarid area of Cameroon and showed that agroforestry, urban and peri-urban forestry, and forest plantations can help to conserve biodiversity and play an important role in climate change mitigation and adaptation. This can be best achieved through landscape studies with a social-ecological systems approach. Furthermore, a more inclusive research approach can facilitate knowledge exchange and dissemination in different directions and make agroforestry adoption more relevant. Dlamini (Chap. 10, Vol 1) while discussing challenges and opportunities of agroforestry research in Africa placed emphasis for devising agroforestry systems that benefit farmers keeping in view the contextual drivers, prevailing conditions, and institutions influencing the trends in agroforestry development.

The tropical agroforestry practices in the arid and semiarid regions (Part II, Vol 1) can have a central focus on domestication of natural forest and fruit trees, sustainability, soil fertility, carbon sequestration, climate change mitigation, and adaptation and socioeconomic well-being. Recent advances in agroforestry for soil conservation and amelioration, domestication of indigenous fruit trees, their transformation and marketing, research opportunities, and policy initiatives have proved the agroforestry potentials in many of tropical and subtropical regions. The widespread adoption of agroforestry technology supported by continued participatory research and dissemination can be instrumental to achieve the goals of poverty alleviation, food security, soil conservation, and environmental sustainability in different regions of Africa, particularly in the scenario of climate change. Some researchers have argued that agroforestry systems are typically multifunctional in the landscape and support sustainable livelihoods for food production, health and nutrition, wood-based energy generation, and income generation in Sub-Saharan Africa (SSA). However, there is need for a holistic valuation of the benefits of agroforestry in terms of provisioning ecosystem services, livelihood benefits, and cultural services. Understanding the contribution of trees to various aspects of livelihoods is needed to support informed decision-making and evidence-based land-use management in SSA. In drylands, there is a need for research in agroforestry to focus more on socioeconomic aspects and address impacts at larger spatial and longer temporal scales.

The role of agroforestry in mitigating climate change is conspicuous, and the climate change impacts on the delivery of tree ecosystem services in the West African Sahel have been analyzed (Sanago et al. Chap 7, Vol 1). Based on long-term data of the past 100 years, the study revealed a decline of rainfall by 20–30%, whereas increase in the mean temperature up to 1.3 °C in the West African Sahel. A significant relationship between tree growth and annual rainfall amounts in Mali and Niger showed that climate change impacts the delivery of tree ecosystem services through the erratic rainfall. The researchers stressed the need for appropriate policies and promotion of sustainable management strategies to enhancement of food and nutrition security of the rural populations in the West African Sahel. Thus, the afforestation of degraded landscapes remains among one of the most effective strategies to mitigate climate change. There is a large potential to regrow trees in croplands and urban areas, highlighting the scope for agroforestry and urban forestry in mitigating climate change. The urban (agro)forestry, though new, proved concept to improve the environment of the surroundings. Recent studies have shown that sewage water can be efficiently utilized to develop landscapes and greenbelts in urban and peri-urban areas (Lal et al. Chap 8, Vol 2). Growing non-food crops such as aromatic and flower-yielding plants with poor-quality waters is viable option. Further, it has been found that agroforestry parklands are the predominant agro-ecosystems in West Africa.

It has been explained in this book that trees in agroforestry systems on degraded lands promote closed nutrient cycling in nutrient poor soils of drylands; however, there is a need for microbial inoculation of tree seedlings with appropriate N-fixing bacteria and mycorrhizal fungi and application of phosphorus fertilizer for their successful establishment. *Faidherbia albida*-based agroforestry practices in sub-Saharan Africa play very significant role. Some workers have presented synthesis of studies relating to the sustainability of *Gliricidia*-based agroforestry systems for improving soil fertility under resource-limited agro-ecosystems. From these studies, it has been found that data are needed on belowground ecological processes, microbial-tree-root interactions, and biodiversity of soil organisms.

Tree-based traditional cropping systems play an important role in production system, and there are opportunities for farm and tribal communities for transforming the traditional systems such as lac (*Laccifer lacca*)-based agroforestry into modern remunerative venture from degraded lands in arid and semiarid regions of India. The lac-based agroforestry can also play an important role to protect host trees in degraded lands and community lands reserved for grazing to control forest degradation. Similarly, silkworm (*Bombyx mori*)- and mopane worm (*Gonimbrasia belina*)-based agroforestry systems can be developed as commercial systems. Some workers stressed the need to recognize entomophagy as a prominent ecosystem service of agroforestry systems on degraded lands. The beneficial role of insects in agroforestry has not attracted the attention of workers because of the adverse effects of insect-pests causing crop losses or failure. For the biological control measures to be effective, it would be useful to harvest pest species such as palm weevils, grasshoppers, and caterpillars in areas of plenty to support food and nutritional security.

The researchers have explored the tropical agroforestry systems of humid and sub-humid regions in Asia, Indian subcontinent, Latin America, and other parts of the world. Van Noordwijk et al. (Chap. 11, Vol 1) have synthesized information on the restoration of degraded land in Southeast Asia by conceptualizing seven degradation syndromes including degraded hillslopes, fire-climax grasslands, over-intensified mono-cropping, forest classification conflicts, drained peatlands, and converted mangroves. For restoration of degraded landscapes, investing in trees as part of their landscapes and farming systems is important besides recognizing the relevance of adopting agroforestry at plot-level, multifunctional landscapes and the interface of agricultural and forestry policies. These workers emphasized appropriate restoration actions through agroforestry by considering local institutions and motivation; rights, knowledge, and know-how of land-use practices, markets for inputs and outputs; local ecosystem services; and global connectivity as a starting point for restoration interventions. The SE Asian experience with agroforestry offers practical lessons to gain insight across a wide range of "degradation syndromes." There is need for a more careful and location-specific diagnosis of land degradation for successful agroforestry interventions. The recently adopted ASEAN agroforestry policy guidelines provide a conducive environment for targeted actions for inducing change at the landscape level.

Various traditional agroforestry systems have also been identified for the restoration of degraded peat swamp area in Indonesia which reflects that incorporation of human dimensions into restoration is crucial to counter the anthropogenic factors driving the degradation of the peatland ecosystem. There is need for rebuilding and documenting traditional agroforestry knowledge and practice for successful natural resources management. Further, it has been found that shifting cultivation has evolved as a part of the culture of the hill people of the region and the agricultural practices are closely linked with the socio-cultural practices and religious beliefs. However, the shortened fallow cycle as practiced in most places in Northeastern India (NEI) is not sustainable; soil erosion, nutrient loss, and other ecosystem disservices resulting with short fallows adversely affected the soil resilience and food insecurity among the shifting cultivators. Therefore, the promotion of tree-based crop production models such as alder (*Alnus nepalensis*)-based traditional agroforestry systems, promotion of traditional betel (*Piper betle*)-based agroforestry, and fertilizer tree-based potential agroforestry practices in slash-and-burn cultivation areas in NEI are important for sustaining agro-biodiversity, forest cover, and soil carbon storage. There is need to introduce an appropriate cash incentive-based mechanism for adoption and promotion of agroforestry systems in degraded fallow lands in NEI among hill farmers. In Africa, short fallows have been improved significantly through participatory mode by growing leguminous *Cajanus cajan*, *Sesbania sesban*, *Tephrosia vogelii*, *Gliricidia sepium*, and *Leucaena leucocephala*. These have been identified as the most promising N-fixing shrubs for this purpose, and *Tephrosia vogelii* is preferred the most because of its pesticidal properties.

Bamboo-based agroforestry has traditionally been managed on family farms because of their great socioeconomic values in rural lives especially in Asia and is currently being promoted as a viable option for social, economic, and environmental benefits. Well-managed bamboo in agroforestry has tremendous potential to contribute to restoration of degraded lands in tropical and subtropical regions. The Asian experiences show that bamboo-based agroforestry is a promising land-use option for enhancing productivity, rising socioeconomic benefits, and sustainable land management in tropical bamboo producing countries.

The role of agroforestry systems in restoration and conservation of biodiversity at the ecosystem and landscape levels, with greater focus on the tropical Latin America, has been assessed. Multistrata systems including home gardens and successional agroforestry systems (AFS) exhibit the highest biodiversity, while more simplified system designs such as perennial crops and silvopastoral systems are characterized by only few trees species representing the low range for biodiversity. AFS such as living fences and windbreaks can provide connectivity in the fragmented agricultural landscape. To fulfill the objectives of biodiversity restoration and conservation, AFS need to increase their structural complexity in terms of number of species and strata. Therefore, AFS should be planned within a broader strategy with due consideration to maintain areas of natural forest in the landscape. Recent studies have shown that greater plant species diversity leads to greater productivity in plant communities, higher nutrient retention in ecosystems, and greater ecosystem stability. The biodiverse agroforestry systems could be useful for recovery of degraded landscapes by implementing environmentally friendly land management practices. The socioeconomic, legal, and political actions can promote biodiversity islands in rural environments. The use of economic instruments, for example, payments for environmental services, improving environmental laws and enforcement to reduce deforestation, regulate logging, conserve on-farm tree cover, and reduce agrochemical use, could play an important role in restoration mechanism.

The functioning of terrestrial ecosystems depends on soil biodiversity as many of the plant interactions take place belowground. The role of soil microarthropods in determining the soil quality of tropical home gardens which are regulated by edaphic factors, abiotic conditions, and land management practices has been explored to some extent. Soil microarthropods being sensitive to soil temperature and soil moisture can alter in number and species composition in relation to seasonal perturbations and soil ecosystem alterations and, thus, can serve as an efficient tool in biomonitoring studies. Soil organisms, including earthworms, are a key component of terrestrial ecosystems; however, little is known about their diversity, their distribution, and the threats affecting soil organisms. Given the role of earthworms and termites as ecosystem engineers, changes in their diversity and distributions in response to management practices clearly need the attention of workers. It is important to analyze their role in nutrient cycling, organic matter decomposition, and formation of soil structure in different types of agroforestry systems. To maximize productivity in agroforestry systems, sequester more carbon in soil, or understand how degraded landscapes will further shift in response to human activities, there is urgent need for greater understanding of biodiversity of soil organisms and their role in ecosystem functioning, particularly in dryland agroforestry systems.

The drivers of change in coastal ecosystem (based on UNEP report of 2006) are land-use changes and habitat loss, fisheries, invasive species, pollution, nutrient loading, and climate change. Climate change is becoming the dominant driver of change, particularly in vulnerable habitats such as mangroves, coral reefs, and coastal wetlands, which are especially at risk from resulting sea level rises and temperature. Agroforestry land-use systems have huge potential for sustainable agricultural production and livelihood security in these regions. Important traditional and site-specific agroforestry systems/practices being followed have been tested in islands and coastal areas my many workers. Opportunities exist for agroforestry-based strategies because of the rich biodiversity and high availability of rainwater ($>$1000 mm). The site-specific farming systems can combine forest and fruit trees, plantation crops, spices, forages, vegetables, and halophytic plants. Integrated farming systems involving fish, shrimps, and different kinds of aquaculture, multi-storeyed plantation-based cropping systems, high-value medicinal, and aromatic plants and spices can be highly remunerative to local people.

Coastal salinity has been a major concern, and in recent years, due to frequent cyclones and phenomenon, rising of sea level due to climate change has aggravated the problem. Aquaculture, horticulture, and plantation-based agriculture has been the primary livelihoods of the people living in the coastal areas of India, but the productivity of all these sectors are much below the national average because of various constraints related to soil, water, and climate. There is much scope for utilizing the potential of halophytes for food, fodder, fuel, oils, healthcare, eco-restoration, bioremediation applications, and their role in restoring the coastal saline soils. In recent years the importance of mangroves has been highlighted, and aquaculture keeping mangroves intact, multi-enterprise agriculture involving fish, shrimp, animals, poultry, mushroom, honey and plantation-based multi-storeyed cropping systems have been advocated for remunerative agriculture. In highly saline areas, domestication of halophytic crops of high economic value is also an option. These areas may open new vistas in agroforestry research.

Among temperate agroforestry systems, riparian buffer systems have the greatest potential to produce biomass while enhancing biodiversity, environmental, and ecosystem services. The sustainability indicators and their influence on biomass production from the long-term ecological research studies on tree-based intercropping and integrated riparian buffer systems in southern Ontario, Canada, over a period of 26 years have been discussed. In tree-based intercropping systems, short rotation woody crops or herbaceous biomass crops can be grown in between the tree rows. Given the current interest on climate change mitigation strategies, the enhancement of C sequestration in terrestrial ecosystems, agroforestry-based biomass production systems can play a major role in sequestering atmospheric CO_2, particularly in roots and soils. Interestingly, soil quality indicators for the improvement of soil fertility in *Nothofagus obliqua* (deciduous) and mixed *N. dombeyi-N. obliqua* (evergreen-deciduous) forests, where a 30-ha silvopastoral trial was established, are analyzed. These studies showed that soil quality was favored by the quality of organic matter in the site dominated by deciduous species, which creates more favorable conditions for the activity of microorganisms, nitrogen dynamic, and C and N content in the light faction of soil. These novel silvopastoral systems can restore the most degraded sites through improvement of the soil quality. Thus, it is important to generate information on soil quality parameters mainly for the planning of long-term, durable silvopastoral practices. Further, the status of temperate rangelands/pastures, factors causing degradation of the grasslands, and suitable agroforestry systems to improve the existing grasslands in western Himalaya have been explored. The existing wastelands in Jammu and Kashmir in India could be potential sites for hill agroforestry systems under TOF for enhancing carbon sinks under CDM and REDD+ mechanism, carbon inventory assessment programs at national and international levels by using latest methods of remote sensing, and GIS integrated with field inventory and advanced algorithms for qualitative and quantitative assessment of TOF resources. The scope of temperate agroforestry is expanding and has attracted the attention of several research workers.

Studies in Australia and Indian subcontinent have shown that well-planned biodrainage on farmers' waterlogged fields by growing cloned *Eucalyptus* and other fast-growing species with high transpiration rates could lower down the water table for cultivation of wheat crops in Community Forestry Program after 3–4 years of growth. The speculation of salinity development in root zone due to evapo-transpiration could not be proved, and experimentation of 6–7 years showed that there was no increase in soil salinity and rather organic carbon and infiltration rate of water increased in vicinity of plantations. There was 3–4 times increase in crop yield due to plantations as compared to no plantations, and farmers could also get additional income after harvesting of trees and the system sequestered carbon in above- and belowground biomass. This is all win-win situation. Similarly, applying appropriate agroforestry techniques highly sodic as well as saline soils could be reclaimed using appropriate silvopastoral systems to the extent that after about 7 years, the land was suitable for arable crops. In large areas sand dunes have been stabilized in arid regions using appropriate agroforestry techniques.

The grazing lands in different regions of the world have become very fragile and unsustainable due to unbalanced utilization of these resources, resulting in large-scale degradation. Protection of existing trees on grazing lands and introduction of nitrogen-fixing trees constitute a sustainable and productive silvopastoral system. Multipurpose tree species can also be adopted in degraded grazing lands with poor vegetation cover or by developing location-specific silvopastoral models. Studies have also been carried out with silvopastoral systems in many Latin American countries and have generated extensive information in adopting and adapting SPS to local conditions. Intensive silvopastoral systems are a good example of a land use in Latin America that can increase the productivity of grazing lands and enhance the generation of ecosystem goods and services. In Latin America, silvopastoral arrangements have the potential to be established in most of the locations where cattle ranching is practiced. In the case of silvopastoral systems explicitly, more research is needed on the physiology of animal-tree interactions; this will allow for the evaluation of these systems with respect to the important and emerging issue of animal welfare. There is need to be mainstreaming of silvopastoral systems in rehabilitating degraded grazing lands to simultaneously address environmental sustainability and meeting the sustainable production objectives from the land. There is need to create awareness among farmers, greater research efforts, and sound implementation of government initiatives for sustainable management of grazing lands.

The potential of agroforestry to improve the economic utilization of highly degraded lands like ravine lands through simultaneous production of food, fruit, fodder, and firewood and carbon sequestration has been explored. Optimum utilization of suitable species of trees, shrubs, and grasses is important in ravine and eroded watershed rehabilitation efforts. Silvopastoral- and fruit-based agroforestry systems involving species of dry areas are the most appropriate options for rehabilitation of such lands. The developmental activities such as railway tracks, road construction, and mine exploration have caused tremendous land degradation. The use of different indigenous and exotic species for the rehabilitation of different types of mines has been identified and grown in many mine spoils. Restoration of limestone quarries in Dehradun, iron ore overburden in Kerala, and coal mining areas of Singrauli in India are successful cases of large-scale post-mining restoration practices in India. However, it is necessary that participatory planning for rehabilitation be carried out for to sustain over a long period of time, otherwise all such measures will be short lived. There is also a need to focus on indigenous species and developing seed banks and nurseries where these resilient plant species can be raised for planting in the areas selected for rehabilitation. For achieving long-term sustainability in the mining area, restoration process must aim to develop tree-based systems with native species.

Urban agroforestry systems are integration of gray and green technologies, capable of recycling and reusing of wastewater and conserving nutrients into biomass, thereby bringing multiple benefits such as fuel wood production, environmental sanitation, and eco-restoration. Still the adoption of urban and peri-urban agroforestry systems by farming community are fewer due to the lack of best suited cropping system. National standards/quality guidelines need to be prepared for the reuse of treated wastewater for agriculture and forest plantation irrigation, taking into account the legal and regulatory framework (e.g., environmental pollution, water quality, food hygiene, and occupational health). Proper intervention of policy support and awareness among the peri-urban farmers will boost the adoption of this integrated system for social, economic, and environmental benefits.

Agroforestry systems in degraded landscapes have a great scope not only of increasing agricultural production and restoration of degraded lands but also of carbon sequestration and mitigating climate change. Though enough data on carbon sequestration has been generated, most of ecological parameters have been ignored. The magnitude of carbon sequestration would vary depending on the climatic and geographical conditions of the area. Soil is a vital component in the functioning of terrestrial ecosystems, and provides a habitat for diverse and interacting populations of soil organisms; decomposition of organic matter is the principal process in soils that recycles nutrients and produces humus, and serves as a critical link with the climate system. Soils deliver provisioning, regulating, and cultural and supporting ecosystem services, which are regulated by the physical, chemical and biological properties of the soil. Soil organic matter, which in turn is governed by biological activities, plays a key role in regulating climate, soil water, and soil biodiversity. In the context of mitigating global climate change, it is important to create a well-quantified carbon sink in agricultural soils worldwide. There is large potential for managing soil carbon in agroforestry systems for climate change mitigation and enhancing the sinks of greenhouse gases. However, for effective soil organic carbon sequestration, there is need to develop agroforestry systems that reduce emission of nitrous oxide from the soil, to measure soil carbon in deep soil layers and to improve efficiency of water and fertilizer use in cropping systems. The inclusion of a diversity of crops might ensure that a diversity of carbon compounds is present in the soil, improving soil carbon.

17.3 Challenges and the Way Forward

We have gone a long way to develop several agroforestry models in different climatic regions of the world, and also site-specific conditions, such as reclaiming salty and waterlogged soils and rehabilitation of ravine lands, improved fallows, use of fertilizer trees to enhance crop productivity in rain-fed dry ecologies, alley cropping, multi-enterprise cropping systems, restoration of mine-spoil areas, restoration of degraded mangrove areas, domestication of indigenous fruit trees, and urban and peri-urban agroforestry. Some of these have been discussed in this book in separate chapters. The forest and landscape restoration is a long-term process that has a focus on the restoration of ecological functionality and enhancing human well-being using a variety of land uses and diverse plant species.

Not surprisingly, as stated earlier, agroforestry systems are playing a vital role for the rehabilitation of degraded lands, biodiversity restoration and conservation, mitigation of climate change through carbon sequestration, livelihood, and food and nutrient security to the people. For agroforestry to succeed, there is need to focus on a system's perspective that can be easily integrated into landscape approaches. The development and upscaling of traditional and improved agroforestry systems need an enabling environment, such as clear land and tree tenure, a strong legal framework, availability of agroforestry product value chains, and involvement of the various stakeholders. For a successful action plan, farmer-friendly policies are needed, both at national and regional levels. To make research more inclusive and relevant outside academia, it is important to create forums involving researchers, local leaders, companies, NGOs, extension workers, and farmers.

Investments in effective restoration of degraded lands should form part of a broader strategy for food security and ecological sustainability. Many of the ecosystem services of agroforestry have not yet been analyzed or neglected in most of studies. The farmers and land managers are not familiar with the range of ecosystem services provided by agroforestry systems, and as a result the perceived value of agroforestry is low. The economic instruments based on ecosystem services need to be developed for greater adoptability of agroforestry for sustainable utilization of degraded landscapes and providing livelihood opportunities to the local people. Climate change-integrated tools along with ecosystem functioning and services are needed to ensure sustainable agroforestry. More rigorous discussion is needed on specificity of linkages between soils and ecosystem services. Models need to be developed with the goal of understanding and predicting key dynamics of soil carbon in relation to ecosystem processes and socioeconomic drivers under scenarios of global and regional change. There is need to facilitate the development of local technical capacities for the collection, production, and distribution of crop and tree varieties and livestock breeds that can tolerate environmental extremes (e.g., drought, heat stress, and salinity) in order to support local communities in adapting to climate change. Investments in effective restoration of degraded lands must form part of a broader strategy for food security and ecological sustainability.

It is both a challenge and an opportunity to the scientific community working in this inter-disciplinary field of agroforestry. To prepare for facing future challenges and seizing the opportunities, scientists need access to synthesized information and develop technologies to assess the environmental benefits being derived from different types of agroforestry systems. The global community is still only in formative phase to recognize the potential benefits of many underexplored 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 landscapes. As we move forward to vigorously explore the potential benefits of agroforestry for solving the problems of restoring degraded landscapes, there is need for successful implementation of suitable agroforestry models and outreaching the information among different stakeholders ensuring food security and environmental sustainability from regional to national and global level. Additionally, if large- scale agroforestry is to be promoted on degraded landscapes, special commitment would be required from governments on the procurement of farm produce on minimum support price, insurance, legal, institutional, and even community arrangements. At the same time, the new paradigms of agroforestry on degraded lands demand management strategies based upon the long-term research collaborations between land managers and scientists with more objective analysis and thus, understanding of their ecological functioning.

Despite the many promises and benefits that agroforestry holds under appropriate conditions, there are also limitations arising from biophysical, socioeconomic, and socio-political conditions, such as land ownership and control and usage rights. 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 like 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. The implementation of agroforestry technologies requires support by specialized extension services that use participatory methods to teach farmers how to implement and manage agroforestry systems compatibly with the aim of restoring their lands and increasing agricultural production both in the short and long terms.

The absence of an effective agroforestry policy in developing countries has been felt since long. The 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 coordination 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. After long deliberations and discussion, the Indian Government launched a forward-looking National Agroforestry Policy in 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. The stakeholders would have to be linked with market, and they would have to be assured the appropriate cost for their produce. Along with the crop insurance, tree component also needs to be insured and all agricultural produces must be brought under minimum support price (MSP) system protected by legal rights. Farmers with small and marginal holdings may adopt cooperative farming well supported by value-addition chain and market. This will ensure the livelihood security to the farming community.

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