P. K. Ramachandran Nair
B. Mohan Kumar
Vimala D. Nair

An Introduction to Agroforestry

Four Decades of Scientific Developments

Second Edition

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Preface

It is not an exaggeration to state that this book has been in the making for more than twenty years. A few years after the first edition of *An Introduction to Agroforestry* was published in 1993, it became clear that it needed improvements in several areas to keep up with the increasing volumes of new research results and development applications in agroforestry in tandem with the new and emerging issues and paradigms. It also became clear over the years that preparing a second edition of the book would entail a thorough revision of the old version and the addition of new chapters on some major topics, such as climate change, that have become prominent since the first edition was published. I (P. K. R. Nair, the first author of this book and the sole author of its first edition) was convinced that I would not be able to undertake such a task until I could concentrate exclusively on it for at least a year. Such an opportunity did not arise until my formal retirement from the University of Florida in 2019. The unexpected lockdowns and travel restrictions imposed by the COVID-19 pandemic in 2020 turned out to be a sort of blessing in disguise that allowed me to stay focused on the task.

About two years ago, when the project got started in earnest, I invited Professors B. Mohan Kumar and Vimala Nair to be involved as my coauthors in this challenging task. All three of us have been close professional collaborators for decades (and Vimala and I are nearing our fiftieth wedding anniversary in 2023). The book embodies our collective efforts in pulling together and synthesizing the large body of literature that had accumulated during the nearly three decades since the first edition and presenting it in a form and format to represent the current level of understanding of the major scientific developments in agroforestry.

The first edition of the book was put together in response to the need felt at the time for a college-level textbook. That basic feature is retained in this edition too. However, agroforestry is an amalgam of several subjects, and the science of agroforestry involves a harmonious blending of both biophysical and socioeconomic sciences; dealing with the vast array of subjects in one book would lead to a too superficial treatment of the individual topics. During my many decades of interactions with students and early-career professionals from different parts of the world, I have noted that the lack of a basic understanding of the biophysical foundations of agroforestry, such as plants, soils, and ecology, impedes those who wish to pursue agroforestry-related careers in development-oriented professions. Furthermore, some issues, such as climate change, soil health, biodiversity, and ecosystem services, which have captured the global community's inquisitive attention over the past three decades, need to be examined and explained in more detail than others. Thus it became imperative for us to highlight the significant benefits and services that agroforestry offers in meeting the targets set out in the United Nations Sustainable Development Goals (SDGs) 2030 (https://sdgs.un.org/goals). We decided to drop the short chapters on experimental designs and farming system methodology, from the first edition, and focus on explaining the principles that underlie the science-based practices in plant, soil, and ecosystem management in agroforestry. Over the decades, we have also been convinced that even in the fifth decade of agroforestry development different groups of professionals entertain divergent, even vague, perceptions on the subject. In the hopes of addressing this problem, we have included, with the splendid cooperation of numerous colleagues from various parts of the world, pictorial presentations of the diversity of agroforestry systems in a variety of ecological and geographical regions.

The book is organized into five sections spanning twenty-four chapters. Chapters 1–3 in the introductory section (essentially the same as it was in the first edition) trace the historical developments leading to the emergence of agroforestry, a narrative of the definition and concepts, and the classification of agroforestry systems based on various criteria. Section II summarizes in eight chapters the major agroforestry systems in the world, with ample photographic illustrations, as indicated above. The biophysical foundations of agroforestry are explained in two sections – Section III (Plant Productivity) and Section IV (Soils). Some of the ecosystem services related to soil fertility management and soil conservation are also included in Section IV. Other major ecosystem services, such as carbon sequestration for climate change mitigation and biodiversity conservation, are the main themes described in Section V. Finally, the concluding section (Section VI) has two chapters, Chapter 23 discussing the role of agroforestry in attaining the SDGs in general and food security in particular, and Chapter 24 provides a broad outlook on agroforestry and land management into the future.

We have tried to reduce the use of scientific jargon to the extent possible to make the book more accessible to those who are relatively less proficient with the scientific literature. For example, we use the commonly understood term *ton* ("t") instead of Mg (1,000 kg) as the unit of mass for expressing crop yields and soil carbon stocks except in some situations. Similarly, the author (authority) names attached to the Latin names of plants are generally not mentioned to avoid the clumsiness of a string of such names appended to the Latin names of some underexploited plants. All other internationally accepted scientific norms, terms, and units are used.

Although a single volume may not satisfy everyone interested in a complex subject like agroforestry, we hope the readers will find this book useful.

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December 2020

Acknowledgments

During the past more than two decades, there have been innumerable requests and persuasions from colleagues around the world for a revised version of the first edition of this book. The ensuing interactions and discussions with a wide spectrum of graduate students, trainees, professionals, and administrators from different countries have influenced our decisions on the scope and content of this book. We are grateful to all those agroforestry enthusiasts at large for their unfailing support and encouragement over the years.

Since the work on the book started in earnest about two years ago, we have been blessed with the outpouring of help and support from numerous individuals whom we contacted with specific requests. The requests covered a variety of subjects such as photographs of different agroforestry systems and components, copies of publications, discussion and clarification on technical points, review of sections of the manuscript, etc. Although the sources of such inputs and resources used in the book have been duly cited, we wish to mention (in no specific order) the names of some such colleagues and acknowledge their help: Ravi Prabhu, Ramni Jamnadass, Roeland Kindt, Susan Onyanko, and Robert Finlayson of ICRAF/World Agroforestry; former ICRAF colleagues Dennis Garrity, Roger Leakey, Chin Ong, and Meine van Noordwijk; Craig Elevitch of the Agroforestry Net, Hawaii; Kaoru Ichikawa, formerly with the UNU/IAS, Tokyo; several colleagues from Brazil including Charles Clement and his associates at INPA, Steel Vasconselas of EMBRAPA, and Robert Miller, Brasilia; Rosa Mosquera-Losada and colleagues of the University of Santiago de Compostela, Spain; Dan Cartledge, Guangzhou, China; Paul Burgess and all the European colleagues associated with the AGFORWARD project; Shibu Jose, University of Missouri; Gary Bentrup, USDA/National Agroforestry Center; Eric Toensmeier and Florencia Montagnini, Yale University; Canadian colleagues including Naresh Thevathasan of the University of Guelph, Scott Chang of the University of Alberta, and Malcolm Cairns; Emmanuel Torquebiau, CIRAD and Christian Dupraz, INRA, France; Pablo Piri, UNPA, Argentina; Francis Dube, Concepción, Chile; A. Arunachalam, Jhansi, India; and Tim Martin, SFRC/IFAS, University of Florida (UF). We also wish to express our special appreciation for the efficient professional help from Raghu Consbruck, Eight Eyes, for the graphic design, drawings, photo conversions, and related works.

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Vimala Nair is grateful to Matt Whiles, Chair, Soil and Water Sciences Department, UF, for his encouragement. P. K. Nair acknowledges the support and cooperation of Terrell ("Red") Baker, Director, School of Forest Resources and Conservation, and other UF colleagues, to complete this work. Vimala and P. K. also greatly appreciate the loving encouragement of their daughters Bindu, Deepa, and Rekha, and their families.

P. K. R. Nair
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Introduction

1 Historical Developments: The Coming of Age of Agroforestry

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Abstract

This introductory chapter traces the historical evolution and development of agriculture and forestry as separate disciplines and chronicles how the demands and challenges of the post-World War II era led to the emergence of agroforestry as an interface between the two. The Green Revolution technologies of the late 1900s paved the way for increasing food crop production substantially in developing countries. On the forestry front, significant gains were attained in enhancing commercial timber production through the establishment of tree plantations. However, these successes were beyond the reach of vast numbers of resource-poor farmers, and the traditional, combined production systems of trees and crops that those farmers have been practicing over generations in many parts of the world were ignored or bypassed. At the same time, tropical deforestation and its disastrous consequences continued unabated. To address these issues, agroforestry was conceived as an integrated approach to combined production systems involving trees and crops on the same unit of land. Parallel to these developments in the tropics, the importance of such combined production systems was recognized in the temperate regions as well following the ecological drawbacks and failures of high-intensity farming and forestry operations. The demand for environmental accountability and application of ecologically

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compatible land-management practices increased when it became clear that the land-use and land-cover changes associated with the removal and fragmentation of natural vegetation for the establishment of agricultural and forestry enterprises led to adverse ecological consequences. Over the past more than four decades, agroforestry has evolved gradually from modest early beginnings to an integrated approach to land management drawing upon the science-based advances in related fields.

1.1 Introduction

In land-use parlance, the adage "a new name for an old practice" may not fit in as well for anything else as it does for agroforestry. To most people, the word agroforestry will sound like a combination of agriculture and forestry. Indeed, that is the essence of agroforestry, no matter what the definition(s) and elaborate characterizations of the term are.

1.2 Cultivating Trees and Crops Together: An Age-Old Practice

Cultivating trees and crops in combination with one another is an ancient practice that is as old as agriculture itself. The so-called tropical homegardens (Chapter 7), for example, are reported to have been associated with fishing communities living in the moist tropical region of about 10 000 B.C. (Nair and Kumar 2006). The long-standing (5000+ years) social, ethnic, and religious reverence accorded to trees and recognition of trees as components of farming systems in India (perceived as agroforestry today) have been recorded in various traditional scriptures and records (Tejwani 1994; Puri and Nair 2004). In Europe, domestic animals were introduced into forests for them to feed on the understory vegetation around 4000 B.C. (Mosquera-Losada et al. 2012). Tracing the history of agroforestry, King (1987) stated that until the Middle Ages it was the general custom in Europe to clear-fell the degraded forest, burn the slash, cultivate food crops for varying periods on the cleared area, and plant or sow trees before, along with, or after sowing agricultural crops. This "farming system" was widely practiced in Finland up to the end of the 19th century and in parts of Germany as late as the 1920s.

Trees were an indispensable part of the Hanunóo farming system in the Philippines; while clearing the forest for agricultural use, they deliberately spared certain trees, which, by the end of the rice-growing season, provided a partial canopy of new foliage to prevent excessive exposure of the soil to the sun, and provided food, medicines, construction wood, and cosmetics (Conklin 1957). Similar farming systems have also been common in many other parts of the humid lowland tropics of Asia. In Central America, it has been a traditional practice to plant more than a dozen species of plants on plots no larger than one-tenth of a hectare. Such an intimate mixture, each with its own distinct structure, imitated the layered configuration of mixed tropical forests (Wilken 1977). In Africa, the dominant form of traditional agriculture involved growing various food crops such as tubers and yams, cereals, and vegetables together under a cover of scattered trees (Forde 1937; Ojo 1966). The Dehesa system of the Mediterranean region of Europe, especially Spain and Portugal, is a centuries-old system of extensive silvopasture (see Chapter 10, Section 10.4.2). Reports on several such examples of traditional land-use practices involving combined production of trees and agricultural species on the same piece of land – which would later be called agroforestry – are available from many parts of the world (Nair 1989). Trees were an integral part of these farming systems, and they were deliberately retained on farmlands to support agriculture. The ultimate objective of these practices was not tree production but food production.

In the light of new and convincing research insights into the ecology of intercropping and multiple cropping since the late 1960s, new efforts were initiated in studying and promoting intercropping with tree crops, leading to efforts such as the now well-known multistory cropping (Nelliat et al. 1974). It was, however, in the late 1970s that these integrated and mostly indigenous forms of growing trees and crops/animals together were brought under the realm of modern, scientific land-use under the banner Agroforestry. Several factors contributed to the push for ecologically and socially friendly management approaches to integrated natural resource management. It started with the understanding of the undesirable environmental consequences of high-input agriculture and forestry practices that focused solely on the economic bottom line (Brown 2004). These developments, which were an integral part of the developments in the overall arena of land-use (agriculture and forestry) since the 1950s, need to be traced against that backdrop.

1.3 Developments in the Agriculture Sector

Agricultural historians may not have a unanimous opinion as to when agriculture began, but it seems there is a consensus that the transition from hunter-gatherer to "farming" happened more than 10,000 years ago. Irrespective of that, two things are clear: agriculture, as practiced today, has only remote similarities to what it may have been when it started, and today it is practiced very differently in various parts of the world. British agriculturist Jethro Tull's invention of drill husbandry (horse-drawn implements such as hoe and seed drill), in the 1730s, is often considered as the beginning of modern agriculture. But the developments during the second half of the 20th century far outweigh all the developments until then (Figure 1.1).

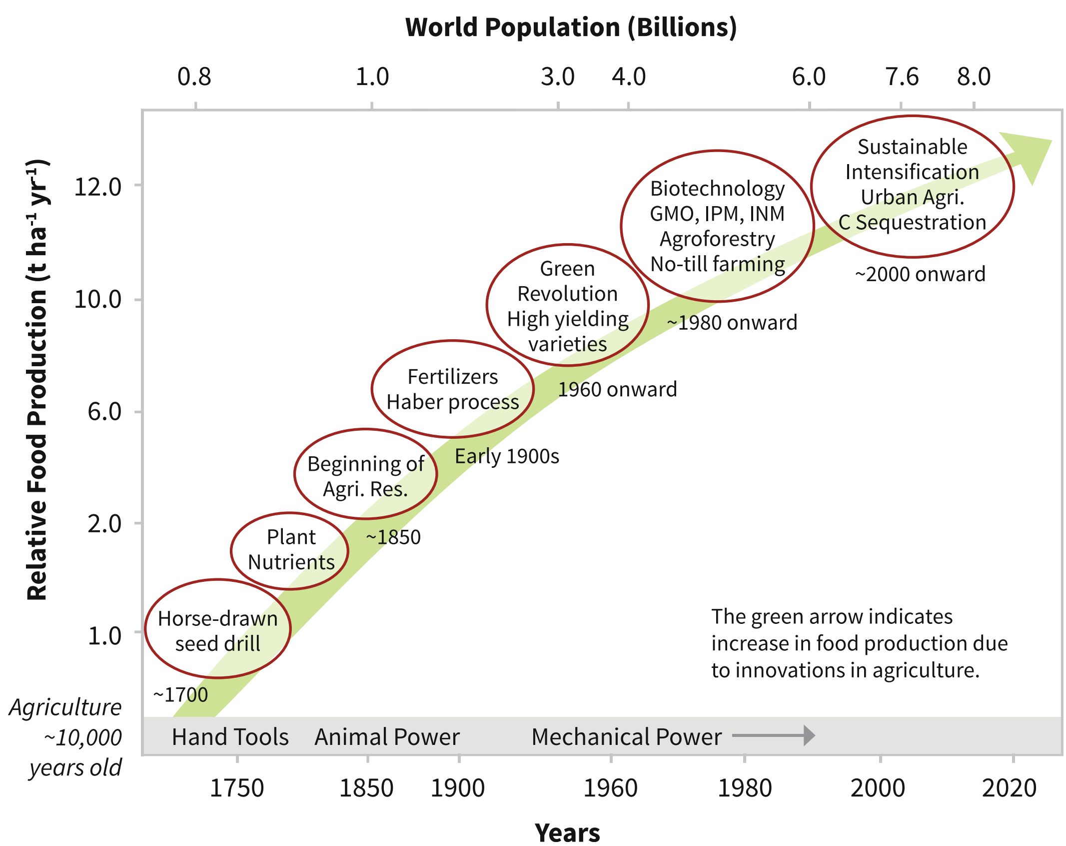


Figure 1.1 Historical developments in agriculture

1.3.1 The Green Revolution

During the second half of the 20th century, the world witnessed dramatic increases in population as well as agricultural productivity. When the newly independent nations of the developing world that were liberated from the colonial yoke were faced with the problem of feeding their millions during the 1950s and 1960s, the policymakers thought the best solution would be to focus on the model of modern intensive monocultural production systems that were successful in the industrialized world. Several food-production technologies were developed with an emphasis on the production of the newly developed high-yielding varieties of cereal crops in monocultural or sole-crop stands with a heavy input of agrochemicals (fertilizers, insecticides, herbicides, etc.), mechanization and irrigation. Collectively called the *Green Revolution*, this package of technologies helped increase the world's food production and avert large-scale hunger and famine in many parts of the world during the late 1970s (Evenson and Gollin 2003; Pingali 2012). While the world's population more than doubled from 2.5 billion in 1950 to 6.1 billion in 2000, the world economy increased more than seven-fold from $ 7 trillion in 1950 (in 2001 dollars) to $ 46 trillion in 2000, worldwide. World grain production tripled from 640 million tons in 1950 to 1,855 million tons in 2000. Out of this 190% increase in grain production, only 30% was the result of increases in area under cultivation, while the remaining 160% was made possible by increases in yield per unit area (world grain yield per ha increased from 1.06 tons in 1950 to 2.79 tons in 2000), brought about by development and adoption of modern agricultural technology. Norman E. Borlaug, who was awarded the Nobel Peace Prize in 1970 for spearheading the development of the Green Revolution, famously articulated that modern agricultural technologies helped save large areas of forest land from clearing ("forest saving agriculture"). His argument was that had the 1950 production practices persisted, an additional 1.1 billion ha of land (forest) would have been needed to produce the total quantity of food grains produced (1,855 million tons) in 2000 (Figure 1.2); thus, the higher grain production per unit area brought about by new agricultural technologies helped spare 1.1 billion ha forest land from being cleared (Borlaug 2007).

1.3.2 The International Agricultural Research Centers (IARCs)

As part of the global efforts in providing the needed research support to enhance agricultural production in developing countries, a network of international agricultural research centers (IARCs) was established in different parts of the world during the late 1970s, under an umbrella organization called the Consultative Group on International Agricultural Research (CGIAR) system (www.cgiar.org). In the beginning, each IARC focused on an individual food crop or a specific ecological region that needed special attention. Thus, separate international centers were established for rice [End Note 1], maize and wheat, potato, etc.; three centers focused on three specific ecological regions, the lowland humid tropics of Africa, the acid soils of Latin America, and the arid and semiarid regions of Asia and Africa; and two centers focusing on livestock production and animal diseases. A complete list of all IARCs (15) and websites of each are available on the CGIAR website. Voluminous literature and publications on the CGIAR system and each IARC are also available.

1.4 Developments in the Forestry Sector

1.4.1 The General Pattern of Forest Resource Utilization Over Time

Forests have served as a home, a spiritual refuge (especially for followers of some religions), and a source of raw materials, since time immemorial. Over the years, forests have been cleared at varying rates in different regions of the world for agricultural and other forms of economic development (see Section 1.4.3 on Deforestation). At the same time, forests are also cherished and protected in many parts of the world for the unique environmental benefits they offer (Díaz et al. 2018). Thus,

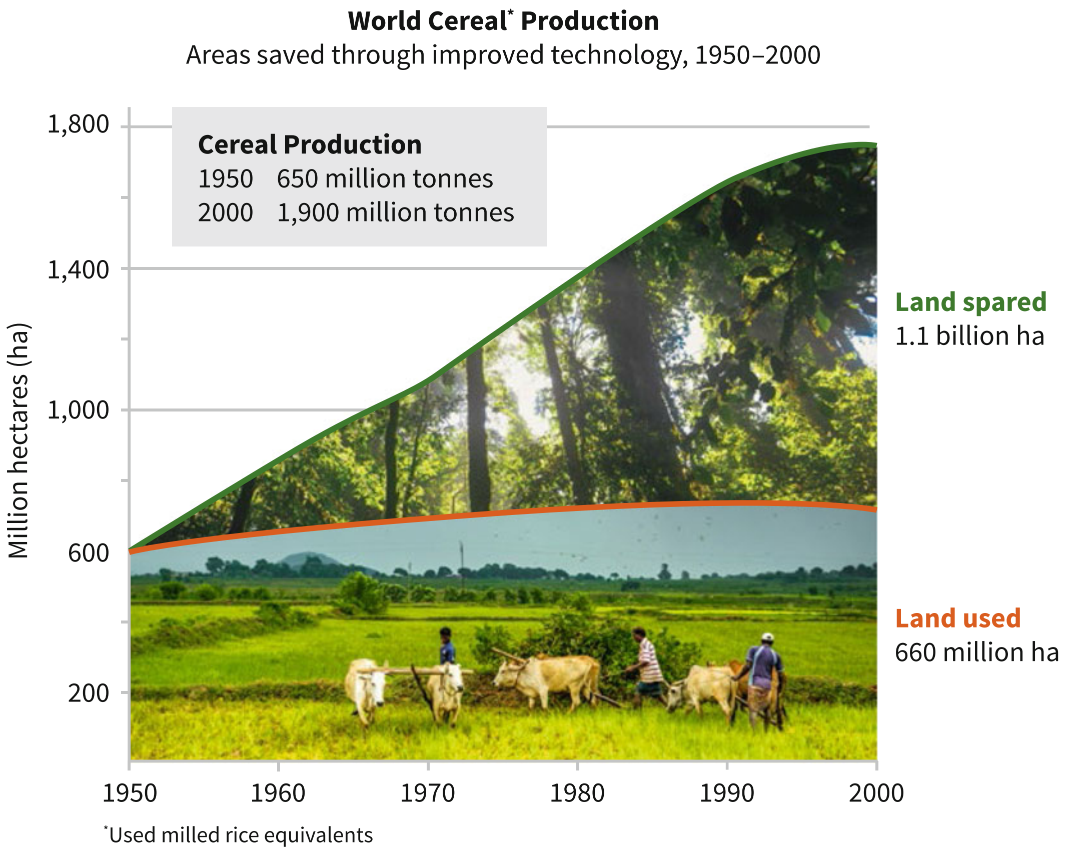


Figure 1.2 Areas saved through improved technology, as conceptualized by Borlaug (2007). The message is that the adoption of Green Revolution technology helped increase food production three-fold and reduce potential deforestation of 1.1 billion ha during 1950–2000

the relationship between humankind and the forest has "a complex and ambivalent history," as Mather (1990) puts it. According to Mather's *forest transition model*, the forest cover of any country over time may follow a U-shaped curve, implying that forested areas that experience deforestation will reach an inflection point and begin to get reforested again. This pattern of forest utilization has followed a sequential trend in different parts of the world (Figure 1.3):

- Phase I: Forests being considered an unlimited resource, with no danger of depletion or need for conservation; indeed, some reduction in the area under forest even welcomed to promote the development
- Phase II: Gradually, forest areas being converted for other uses, primarily agriculture
- Phase III: Concerns being expressed about the rapid rate of forest depletion; calls for conservation become increasingly strong and loud
- Phase IV: A phase of government action and legislative measures to arrest further destruction; the trend of destruction is either reversed or continued depending on how effectively the legislation is implemented.

Different countries have reached different stages of this model at various time-periods, and the duration of the phases vary among countries.

An excellent example of the successful operation of the model is provided by the developments in forestry in the United States during the past 500 years. When the settlers arrived in the USA, forests were abundant and were considered a hindrance to development (Phase I). Soon, forest clearance, primarily for agriculture, started vigorously (Phase II). Fears of timber famine and calls for careful management were voiced starting from the late 19th century and continued into the early 20th century (Phase III). The first Forest Act of 1891 led to the establishment of

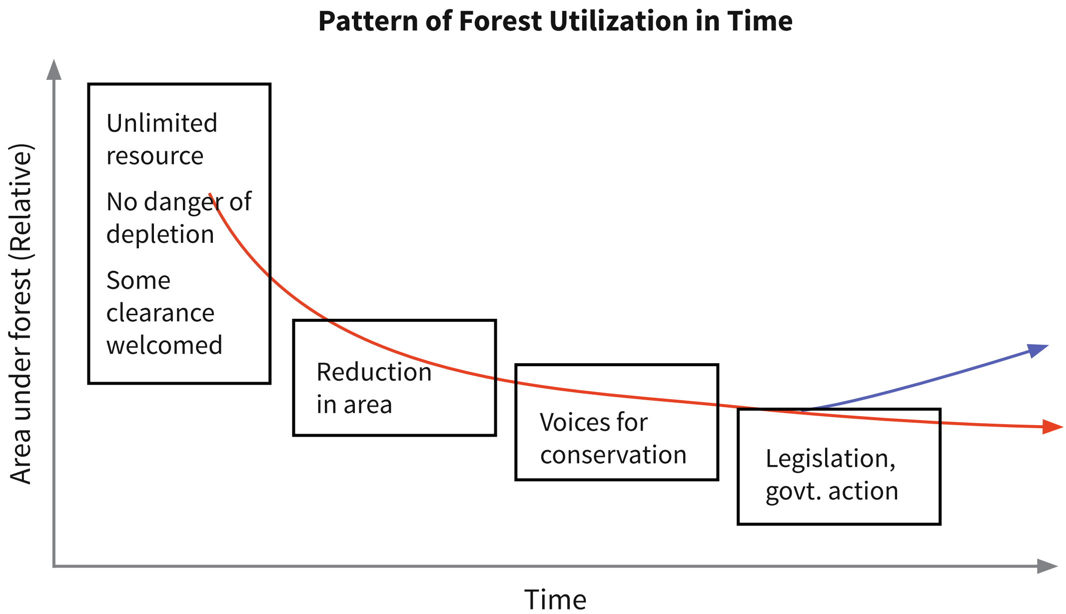


Figure 1.3 A generalized pattern of the sequential trend of forest utilization in different parts of the world
Source: Adapted from Mather (1990)

Forest Reserves (later called National Parks). Gifford Pinchot (1865–1946), the founding chief of the US Forest Service, famously stated in 1905 that "where conflicting interests must be reconciled, the question shall always be decided from the standpoint of the greatest good for the greatest number in the long run," implying the need for conservation and sustainable management of forest resources. Further, addressing the American Forestry Congress in 1905, President Theodore Roosevelt declared "if the present rate of forest destruction continues, with nothing to offset it, a timber famine is inevitable." In 1920, the US Forest Service pointed out that the logging rate was nine times the rate of growing new wood. Following the enactment and implementation of strict forestry laws and their proper implementation with the cooperation of the government, private landholders, and forest industry, the annual growth of timber exceeded the annual cut rate by 1960. This remarkable reversal is often cited as a classic example and model for other countries.

On the other extreme is the case of Greece and other Mediterranean regions, where forest destruction started more than 2000 years ago. Although laws were enacted to address the issue, they were weak, to begin with, and were not effectively implemented. Consequently, much of the original forest cover was lost and degraded beyond recovery, leaving only the scrubby vegetation of today that covers about a meager 5% of land compared to 50% 2000 years ago. Unfortunately, many developing nations, especially in Africa, are undergoing this situation of forest mismanagement and degradation today. It is important to note, however, that even when forest decline trends have been reversed, what is restored is the timber production potential of the forest; much of the aesthetic and conservation values of natural forests, once lost, cannot be restored.

The study of forests is fascinating but extremely complex, too, such that different groups of people studying and describing different aspects or components of forests and forestry come up with different perceptions, but none provides a clear, holistic picture because the whole is more than the sum of its parts. Poet

John Godfrey Saxe's description of six blind men describing an elephant is apt to portray the state of the study of forests:

> *"It was six men of Indostan, to learning much inclined,*
> *who went to see the elephant (Though all of them were blind),*
> *that each by observation might satisfy his mind.*
> *And so these men of Indostan, disputed loud and long,*
> *each in his own opinion, exceeding stiff and strong.*
> *Though each was partly in the right, and all were in the wrong!*
> *So, oft in theologic wars, The disputants, I ween,*
> *tread on in utter ignorance, of what each other mean, and*
> ***prate about the elephant, not one of them has seen!"***
> (Adapted from P. Holmgren: The new global assessments and the forest, CIFOR, Sept 2015, forestsnews@cgiar.org)

1.4.2 Major Forestry Research and Development Initiatives Since the 1950s

Although the global area under agriculture and forestry are somewhat equal (agriculture about 1.5 billion ha or 36 % of the land suitable for crop production; forestry 33%:

World Agriculture: Towards 2015/2030 – An FAO perspective www.fao.org/docrep/005/y4252e/y4252e06.htm), agriculture occupies a much more dominant position and receives a lot more attention than forestry in terms of the number of people involved, resource allocation, and research infrastructure in almost all countries around the world. The Green Revolution in agriculture signified an excellent illustration of the power of science to deal with world problems and the world community's collective response to grave challenges posed by rapid population increases and staggering food shortages in many of the newly independent states in Asia and Africa during the post-World War II era. Nothing comparable to that has happened in the forestry sector. Research and development in forestry continued to be focused on enhancing timber production, primarily through the establishment of plantations of a select few timber species and development of their high yielding cultivars and varieties as well as silvicultural practices for maximizing timber production (Figure 1.4). Except for a few prominent institutions (for example, the Forest Research Institute in Dehra Dun, India, originally known as Imperial Forest Research Institute, founded in 1906 under the British colonial rule), forestry research of any significant magnitude was not common in most developing countries. In the administrative set up too, forestry was a subset of the broad term "Agriculture" in most countries, a legacy that continues even in the international arena (Forestry is a part of the United Nations Food and Agricultural Organization – FAO).

Plantation forestry that originated in Europe and Japan around 1800 (Sedjo 2001) continues to be the main activity in forestry even today. In the tropics, teak (*Tectona grandis*), a native of South-

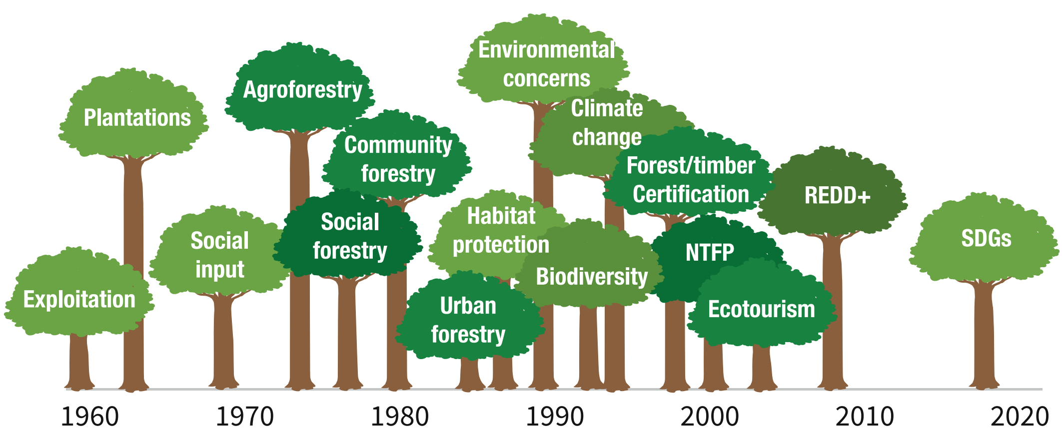


Figure 1.4 Tropical Forestry: Issues, Concerns, and Paradigms, 1960–2020

Figure 1.5 The Connolly's Plot: One of the earliest teak (*Tectona grandis*) plantations in the world. Established in the 1840s in Nilambur, Kerala, India, and declared as a permanent preservation plot by the Kerala Forest Department in 1943. (Photo: PKR Nair 2018, December)

and Southeast Asia and valued for its high-quality wood, is perhaps the first tree species to be grown in a plantation; and, the first-ever teak plantation (Figure 1.5) was established at Nilambur, Kerala, India, in 1840 (Evans 1982). According to FAO SOFA (*State of the World's Forests*) 2020 (FAO/UNEP 2020), plantations account for only about 7% of the total global forest area, but about 50% of the world's timber production. The economic importance of plantation forestry needs no further explanation. The common species grown in forest plantations are very few, with the genera *Pinus* (pines) and *Eucalyptus* being the most popular. Some exceptionally valuable tree species that are grown in plantations need a special mention here, although the area and distribution of such specialty species are relatively limited and localized. The Japanese cedar (*Cryptomeria japonica)* is one such species, valued for its special quality timber and as a hallmark of status in Japanese society, is perhaps the most intensively managed timber species in the world (Figure 1.6). Another one is the famed sandalwood tree (*Santalum album*) of the tropics, which is grown in both plantations and in association with other species; also see Chapter 13, Section 13.4.3.

By the end of the nineteenth century, establishing forest plantations had become an important strategy for practicing a land-management system called *Taungya,* considered to be one of the forerunners to agroforestry. It involved planting the preferred tree species in plantations, usually using available unemployed or landless laborers who would be looking for land to produce food and often encroaching forest land. In return for performing the forestry tasks, the laborers would be allowed to cultivate the land between the rows of tree seedlings to grow agricultural produce. The practice is reported to have originated in the 1850s in Myanmar (Burma), then a part of the British Empire (See Chapter 5 for more details).

1.4.3 Deforestation

History is replete with the harrowing tales of rich and abundant tropical forests being destroyed for their valuable timber and other natural resources by greedy dictators, leading to disastrous soil degradation and extreme impoverishment of several countries such as Haiti (Figure 1.7) and many

Figure 1.6 Japanese cedar (*Cryptomeria japonica*) plantations in Japan are arguably the most intensive silvicultural operation in the world. (Photo: PKR Nair 2000)

Figure 1.7 Deforestation: Haiti: A harrowing tale of the disastrous consequences of deforestation. The hillsides of the country, once covered with the luxurious canopy of valuable tropical timber trees have been ravaged by rampant deforestation during the early 19th century, making the country the poorest in the western hemisphere and one of the poorest in the world. (Photo: M. Bannister, 1987)

Figure 1.8 Deforestation in Kalimantan, Indonesia. (Photo: PKR Nair 1984)

nations in Africa and Asia (Figure 1.8) during the 20th century. When environmental concerns became very conspicuous on the global scene since the 1970s, deforestation of the world's tropical region attained top listing on the agenda of almost all environment-related discussions at all levels. Even today, it continues to dominate the news – both at various local and international levels ever since, with no end in sight. The recent (2020) escalation in deforestation rates of the Amazon basin of Brazil (Figure 1.9), attributed to the policy changes consequent to Brazil's administration change in late 2018 has earned widespread public outrage and condemnation the world over as reported and reverberated in all leading global news services and publications such as *The Economist*, "Deathwatch for the Amazon," 3 August 2019; and, *Time*, Special Climate Issue, 23 September 2019, Section South America, pp 68 – 87 (Figure 1.10).

Universally accepted definitions and estimates of the rates of deforestation, however, are lacking, which has added to the lack of clarity that prevailed over the discussion of these issues for so long. The World Bank defined deforestation as the disturbance, conversion, or wasteful destruction of forest lands, assembled statistics on the extent and progression of deforestation in the tropics during the 1970s and 1980s, and estimated the then prevailing rates at about 12 million hectares per year (World Bank 1991; Sharma 1992). The FAO, on the other hand, based on its preliminary estimates from the 1990 assessment, reported that the actual rate of deforestation during the 1980s was about 50 percent higher, 17.1 million hectares annually (Matthews and Tunstall 1991). One of the main reasons for these differences is that many of the assumptions, based on which estimates of the extent of tropical deforestation were made, have proven false, and very little effort has been made to update the information systematically (World Resources Institute 1990). The most widely quoted datasets of deforestation are those in the FAO's SOFO (*State of the World's Forests*) reports published periodically, the most recent one being the SOFO

Figure 1.9 Deforestation in the Amazon region of Brazil. Most discussions and reports on tropical deforestation since the 1960s start with the destruction of the Amazon forests in Brazil, which continues unabatedly at a reported annual rate of about 1% (see Figure 1.11)

Figure 1.10 Forest clearance for shifting cultivation, DR Congo. The practice of shifting cultivation (Chapter 5) is considered to be the primary reason for tropical deforestation. The photo shows a field planted with cassava (*Manihot esculenta*) and maize (*Zea mays*) in a recently burned patch of secondary forest near Yangambi, Tshopo Province, DR Congo (rainy season May 2012), with different stages of secondary forest regrowth as well as an old-growth forest in the background. Source: Pieter Moonen, http://dx.doi.org/10.1016/j.landusepol.2016.07.019 (with permission)

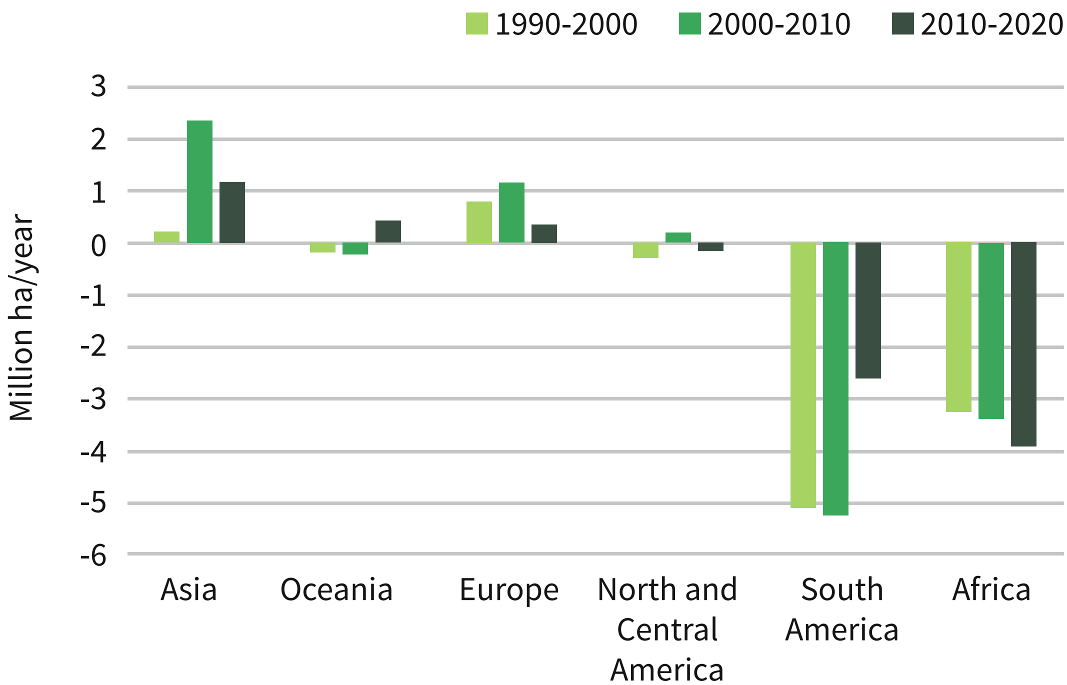


Figure 1.11 Global trends in deforestation: Changes in net forest areas, million hectares per year, in different regions of the world during 1990–2020. Source: FAO (SOFO, State of the World's Forests), 2020

2020: FAO/UNEP (2020), https://doi.org/10.4060/ca8642en. Despite the differences in estimates by different agencies, there has been no divergence of opinion that tropical deforestation rates were high in regions with large areas of remaining forests in Latin America (The Amazon Basin), Africa (Congo Basin), and Southeast Asia (Figure 1.11). The SOFO 2020 states: "*Since 1990, it is estimated that some 420 million hectares of forest have been lost through conversion to other land uses, although the rate of deforestation has decreased over the past three decades. Between 2015 and 2020, the rate of deforestation was estimated at 10 million hectares per year, down from 16 million hectares per year in the 1990s. The area of primary forest worldwide has decreased by over 80 million hectares since 1990*." There has been no difference of opinion on the consequences of deforestation either: that deforestation causes a decline in the productive capacity of soils, accelerated erosion, siltation of dams and reservoirs, destruction of wildlife habitats, and loss of plant genetic diversity (World Bank 1991). It is also generally agreed that the main causes of deforestation are population resettlement schemes, forest clearance for large-scale agriculture, forestry enterprises and animal production, and in particular, shifting cultivation (see Chapter 5). As early as 1982, an FAO estimate showed that shifting cultivation was responsible for almost 70 percent of the deforestation in tropical Africa and that forest fallows resulting from shifting cultivation occupied an area equivalent to 26.5 percent of the remaining closed forest in Africa, 16 percent in Latin America, and 22.7 percent in tropical Asia (FAO 1982). The SOFO 2020 states: "*Agricultural expansion continues to be the main driver of deforestation and forest fragmentation and the associated loss of forest biodiversity. Large-scale commercial agriculture (primarily cattle ranching and cultivation of soya bean and oil palm) accounted for 40 percent of tropical deforestation between 2000 and 2010, and local subsistence agriculture for another 33 percent*."

1.4.4 People-Oriented Forestry Programs

In addition to plantation forestry, two dominant and interconnected issues impacted the directions in forestry development especially in the tropics during the second half the 20th century: the gradual acceptance and recognition of the importance of social and societal aspects of forestry (Westoby 1989) leading to the initiation of several people-oriented forestry programs, and the recognition of the increasing spread of deforestation and its devastating consequences. At the beginning of the 1970s, serious doubts and concerns began to be expressed that the basic needs of the poorest, especially the rural poor, were neither being considered nor adequately addressed in forestry development programs. Although the Green Revolution led to a substantial increase in food grains, it became quite clear and widely recognized that many of the green revolution technologies that placed a heavy demand on the increased use of fertilizers and other costly inputs were beyond the reach of resource-poor farmers in the developing countries. Most of the IARCs and the national programs focused on individual crops such as rice, wheat, maize, and potato[End Note 1], and production technologies for monocultural or sole-crop production systems of these crops. However, the farmers, especially the poorer ones, often cultivated their crops in mixed stands of more than one crop, and sometimes crops and trees; in such circumstances, the production technologies developed for individual crops would seldom be applicable. These shortcomings were recognized widely, especially by influential policy-makers. For example, Robert McNamara, the President of the World Bank confronted these concerns quite clearly when he wrote (McNamara, 1973): *"Of the two billion persons living in our developing member countries, nearly two-thirds, or some 1.3 billion, are members of farm families, and of these are some 900 million whose annual incomes average less than $100...for hundreds of millions of these subsistence farmers life is neither satisfying nor decent. Hunger and malnutrition menace their families. Illiteracy forecloses their future. Disease and death visit their villages too often, stay too long, and return too soon. The miracle of the Green Revolution may have arrived, but, for the most part, the poor farmer has not been able to participate in it. He cannot afford to pay for the irrigation, the pesticide, the fertilizer, or perhaps for the land itself, on which his title may be vulnerable and his tenancy uncertain."* Against this backdrop, the World Bank formulated a Forestry Sector Policy paper in 1978, which was designed to assist the peasant and the ordinary farmer by increasing food production and conserving the environment as much as it helps the traditional forest services to produce and process wood (Spears 1987). At around the same time, the FAO too independently undertook a reassessment of its forestry projects and redirected its focus and assistance in the direction of the rural poor (FAO 1976). As Westoby (1989) would later express it: *"Just because the principal preoccupation for the forest services in the developing world has been to help promote the miscalled forest and forest industry development, the much more important role which forestry could play in supporting agriculture and raising rural welfare has been either badly neglected or completely ignored."* The FAO policy focused on the benefits that could accrue to both the farmer and the nation if greater attention were paid to the beneficial effects of trees and forests on food and agricultural production, and advised land managers in the tropics to incorporate both agriculture and forestry into their farming system, and "eschew the false dichotomy between agriculture and forestry" (King 1979).

While these strands of forest policy reforms were evolving independently in the leading international funding agency and the specialized agency of the United Nations, several tropical land-use experts and institutions were involved simultaneously in research efforts to support the implementation of the new policies. Notable among them was the renewed and heightened interest in the concepts of intercropping and integrated farming systems. It was being demonstrated, for example, that intercropping may have several advantages over sole cropping. Preliminary results from research in different parts of the world had indicated that in intercropping systems more effective use was made of the natural resources of sunlight, land, and water; that intercropping systems might have beneficial effects on pest and disease problems;

that there were advantages in growing legumes and non-legumes in mixed stands instead of in conventional single-species stands; and that, as a result of all these, higher yields could be obtained per unit area when multi-cropping systems were compared to sole cropping systems (Papendick et al. 1976). Building upon the success of these scientific studies, agricultural scientists began exploring with renewed interest the scientific foundations and production potential of traditional practices of intercropping in the stands of tree crops. The emergence of new management approaches such as multi-tier (multistoried) cropping with coconuts in India (Nelliat et al. 1974; Nair 1979, 1983) and shade-management and nutrient dynamics under shaded perennial species such as coffee in Central America under the initiative of CATIE (*Centro Agronónomico Tropical de Investigación y Enseñanza* = Tropical Agricultural Research and Education Center; www.catie.ac.cr), Turrialba, Costa Rica (De las Salas 1979; Budowski 1983) are examples of this. The role of trees and shrubs in maintaining soil productivity and controlling soil erosion was another major research initiative during that period (Young 1989). Livestock management experts also began to recognize the importance of indigenous tree-and-shrub browse in mixed farming and pastoral production systems (Torres 1983).

The challenges and consequences of deforestation were recognized and felt as early as the 1970s. Several studies and efforts were made to reduce the extent of deforestation and suggest alternative land-management strategies. Although the problem, unfortunately, was not contained, several seemingly sound strategies evolved. Ecologists produced convincing evidence of the positive influence of forests and trees on the stability/resilience of ecosystems, leading to the call for measures to protect the remaining forests, introduce more woody perennials into managed land-use systems, and change farming attitudes. Studies carried out by anthropologists and social scientists on farmer attitudes to improved land-use systems showed the importance of mixed systems in traditional cultures and highlighted the need to build upon these practices when developing new approaches (Conway 1985; Chambers and Carruthers 1981; Raintree 1987). These studies and revelations that started in the 1970s not only brought out several scenarios and viewpoints on a complex question, but also a crucial topic that would later become a dominant theme in international and national development paradigms: sustainability. Are modern technologies causing increasing damage to the ecological foundations of agriculture, such as land, water, forests, biodiversity, and the atmosphere? In other words, in our efforts to provide for the needs of the present, are we compromising the ability of future generations to provide for themselves: are these technologies sustainable? What lessons can be learned about sustainability from the integrated land-use systems that have traditionally been practiced in different places around the world?

1.5 Formation of ICRAF and the Institutionalization of Agroforestry

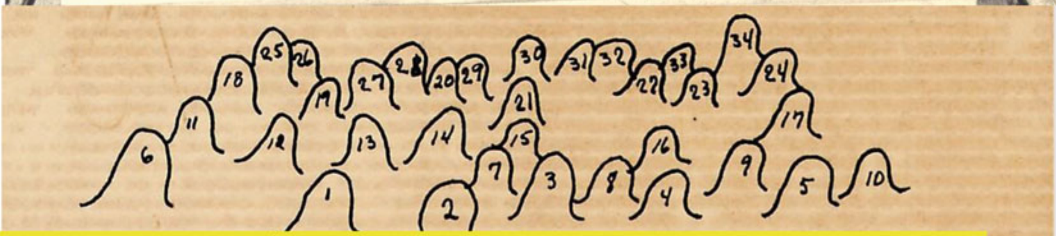
This confluence of people, concepts, and institutional changes in the 1970s provided the material and the impetus for the initiation of focused efforts on promoting the combined production of trees and crops on the same parcel of land. Although many individuals and institutions have made valuable contributions to the understanding and development of the concept, the most significant single initiative that contributed to the development of agroforestry came from the International Development Research Centre (IDRC) of Canada. In July 1975, the IDRC commissioned John Bene to undertake a study to:

- identify significant gaps in world forestry research and training
- assess the interdependence of forestry and agriculture in low-income tropical countries and propose research leading to the optimization of land use
- formulate forestry research programs which promise to yield results of considerable economic and social impact on developing countries
- recommend institutional arrangements to carry out such research effectively and expeditiously, and
- prepare a plan of action to obtain international donor support.

Bene's team concluded that top priority should be given to combined production systems that would integrate forestry, agriculture, and/or animal husbandry to optimize tropical land use (Bene et al. 1977). Their report stated: "*It is clear that the tremendous possibilities of production systems involving some combination of trees with agricultural crops are widely recognized, and that research aimed at developing the potential of such systems is planned or exists in a number of scattered areas. Equally evident is the inadequacy of the present effort to improve the lot of the tropical forest dweller by such means. A new front can and should be opened in the war against hunger, inadequate shelter, and environmental degradation. This war can be fought with weapons that have been in the arsenal of rural people since time immemorial, and no radical change in their lifestyle is required. This can best be accomplished by the creation of an internationally financed council for research in agroforestry, to administer a comprehensive program leading to better land-use in the tropics.*" In short, there was a shift in emphasis from forestry to broader land-use concepts, which were perceived as having immediate and long-term relevance.

It was apparent that despite the growing awareness of the need for information on which agroforestry systems might be effectively based, very little research was being undertaken, and whatever little that was being conducted was haphazard and unplanned. Recognizing this, the IDRC Project Report recommended the establishment of an international organization, which would support, plan, and coordinate, on a worldwide basis, research combining the land-management systems of agriculture and forestry. This proposal was generally well-received by the international and bilateral agencies. Subsequently, a Steering Committee consisting of representatives of various institutions and some experts at large was constituted to move the agenda forward (Figure 1.12) in the same way in which the establishment of several CGIAR institutions had been initiated. Following a series of consultations and discussions, the International Council for Research in Agroforestry (ICRAF) was established in 1977. In 1978, the Council moved to its permanent headquarters in Nairobi, Kenya. In 1991 it was renamed as "Centre" (instead of Council) and was formally admitted to the CGIAR Group. Today it is known as the World Agroforestry Centre or World Agroforestry (www.icraf.cgiar.org), but the acronym ICRAF, which is the term in the legal documents, stands. The establishment of ICRAF in 1977 signified the institutionalization of the ancient practice of agroforestry and the beginning of "modern" agroforestry.

By the mid-20th century, the importance of combined production systems was echoed in industrialized countries too. J Russell Smith's classical work "*Tree Crops: A Permanent Agriculture*" (Smith 1929, 1950) created a "new" wave of interest in such land-use systems. He argued that "an agricultural economy based almost entirely upon annual crops such as corn and wheat is wasteful, destructive of soil fertility and illogical" (see Chapter 10). However, it was not until the late 1970s to early1980s that the push for ecologically and socially friendly management approaches such as integrated natural resource management, the principles of which are encompassed in agroforestry, gathered momentum. It started with an understanding of the undesirable environmental consequences of high-input agriculture and forestry practices that focused solely on the economic bottom line (Brown 2004: www.earth-policy.org). Their demand for environmental accountability and application of ecologically compatible management practices increased when it became clear that the land-use and land-cover changes associated with the removal and fragmentation of natural vegetation for the establishment of agricultural and forestry enterprises led to adverse ecological consequences. Gradually, agroforestry initiatives sprung up in North America in the late 1980s (Garrett 2009). The Association for Temperate Agroforestry (AFTA: http://www.aftaweb.org) formed in 1991 has been organizing biennial conferences since then (in alternate years); the 16th was in Corvalis, Oregon, in 2019. This momentum in agroforestry has spread to other industrialized regions of the world such as Europe



PARTICIPANTS IN ICRAF STEERING COMMITTEE MEETING, AMSTERDAM, June 28, 1977

No.	NAME	No.	NAME	No.	NAME
1	A. Samper	13	J.G. Bene, IDRC	24	J. Groulez, CTFT
2	E. Troeleman, RTI	14	translator	25	G.J. Vervelde, Neth.
3	J.H. Hulse, IDRC	15	L. Marcano, Ven.	26	G. Lessard, IDRC
4	W.A.C. Mathieson,UNDP	16	D. Dumith, Ven.	27	R. Olembo, UNEP
5	K. Soels, Netherlands	17	E.Giordano, Italy	28	A. Pieters, Belgium
6	T. Chandler, IDRC	18	D.F. Peterson,USA	29	G. Koopman, RTI
7	T.J. Marlay, IDRC	19	M. Mensah	30	J.G. Ohler, Neth.
8	J.C. Madamba	20	P.K.R. Nair	31	K.F.S. King, FAO
9	P. Ladouceur, CIDA	21	R. Pasquier, Swit.	32	J. Wassink, RTI
10	H. Kruijssen, Neth.	22	G.Winckler, Germ.	33	S. Appelqvist,Finl.
11	translator	23	B. Nottola, Italy	34	H. Huffnagel, RTI
12	H.W. Beall, IDRC				

Figure 1.12 ICRAF Steering Committee Meeting 28 June 1977. The creation of ICRAF (International Council – *later renamed as Centre* – for Research in Agroforestry), now called World Agroforestry, marked the institutionalization of agroforestry and initiation of agroforestry research on a global stage. PKR Nair, the primary author of this book, is in the back row, circled

(European Agroforestry Federation, EURAF, www.eurafagroforestry.eu: Riguero-Rodrigues et al. 2008; Mosquera-Losada et al. 2012) and Australia (Agroforestry.net.au: George et al. 2012) and New Zealand (Knowles 1991).

Following or along with these international efforts, several programs in agroforestry research, education, and development were initiated in various countries and regions. Agroforestry has been a major focus of activities of CATIE, Costa Rica, since the late 1970s; although focused primarily on the Central American region, CATIE has, over the decades, attained a prominent global leadership role in agroforestry research and development. Several countries have their national programs in agroforestry as well. Among these, those in two large, tropical/subtropical countries, India and Brazil, in both of which agroforestry programs were initiated during the late 1970s, merit special mention in terms of the diversity of programs in various ecological regions that are available in both countries. Specific institutions dedicated to agroforestry research and development have been established in both India and Brazil under the overall federal government agencies such as the ICAR (Indian Council of Agricultural Research), ICFRE (Indian Council for Forestry Research and Education), and EMBRAPA (*Empresa Brasileira de Pesquisa Agropecuária* = Brazilian Agricultural Research Enterprise: https://www.embrapa.br). Both these countries have national policies and development programs as well as professional societies with their periodic congresses and ensuing scientific and technical publications on different aspects of agroforestry. Several other countries also have national programs and initiatives in agroforestry commensurate with their overall size and ecological spread.

Thus, from modest early beginnings in the late 1970s, agroforestry has evolved as a land management discipline over the past more than four decades. Academic and scientific programs sprang up in various institutions around the world and agroforestry is taught as a part of forestry- and agriculture-degree courses in many universities in both the developing and industrialized world. A scientific journal, *Agroforestry Systems* (publisher: Springer) exclusively devoted to research in agroforestry was founded in 1982. Besides, agroforestry research results are now published in numerous other scientific journals in agricultural, biological, social sciences, and other related fields. A series of World Congresses in Agroforestry initiated in 2004 has held four such global events at five-year intervals (Florida, USA, 2004; Nairobi, Kenya, 2009; New Delhi, India, 2014; and Montpellier, France, 2019), attended by an average of about 1,000 participants from around 100 countries each.

Today, agroforestry is not merely the handmaiden of forestry or agriculture. It is being used as an integrated land-management system particularly by smallholder farmers around the world. The well-recognized role and potential of agroforestry for food security, poverty alleviation, ecorestoration, and climate-change mitigation make it an essential component of rural development agendas at local, regional, and global scales. Indeed, agroforestry has come of age conspicuously as a science-based land-use option.

EndNote

EndNote [1]. Latin names of plants are included only to the extent deemed necessary for the proper understanding of the species. For that reason, Latin names are avoided in the text for the unambiguous names of common food crops (such as maize, potato, rice, and so on) and perennial species (such as cashew, coconut, coffee, pines, and so on).

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2 Definition and Concepts of Agroforestry

Contents

Abstract

The term agroforestry was coined in 1977 as part of the early international efforts to initiate research on integrated production systems involving crops and trees. Numerous discussions and arguments were held during those early days to define and characterize agroforestry, and several definitions were proposed. This chapter reviews the development of the concept and the many definitions that had been proposed. The basic concept that is common to all diverse agroforestry practices is the purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit. Today, agroforestry represents the modern, science-based approach to harnessing the sustainability attributes and production benefits of time-tested practices of integrating trees in agricultural systems for a variety of objectives. Its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use has received increasing attention in development programs and paradigms around the world.

2.1 Introduction

It is clear from the previous chapter that agroforestry is a new name for a set of old practices. The word was coined in 1977 during the deliberations that led to the establishment of ICRAF described in Chapter 1 (Section 1.4; Figure 1.9), but it took a while for it to attain acceptability in international land-use parlance. This chapter reviews the development of the concept and the many definitions that had been proposed before the word agroforestry became firmly established in the literature and widely recognized.

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_2

2.2 Evolution of Definitions of Agroforestry

The international initiatives to establish an institution (ICRAF) to promote agroforestry were well-received by various development and research agencies and organizations around the world. Along with such expressions of support to the concept, however, numerous opinions, concerns, and even strong objections were raised about the word itself. Some questioned the grammatical propriety of the word agroforestry and argued that if the words "agri" (for agriculture) and forestry are combined, it should be "agriforestry" (Stewart 1981); and, if it is written as agroforestry, that should be hyphenated (agro-forestry). Indeed, even in the 1990s, i.e., almost two decades after the beginning of the popularization of the concept of agroforestry, the term used to be written in hyphenated form (agro-forestry) in FAO documents and records of national forestry institutions of several countries. Then there was a school of thought that agro-sylviculture or agri-silviculture rather than agroforestry should be the "correct" term. Today, the term agroforestry is so well established that efforts to replace it with some other word to embody the same concepts will be futile.

Although the objections to the word itself faded gradually, the question "what is agroforestry" used to come up for much longer. Even those who were supposedly experienced and knowledgeable about agroforestry in the late 1970s and early 1980s were unable to clearly define agroforestry. As a manifestation of this lack of precision, most writings on agroforestry during that period contained at least one definition and often some imaginative and fascinating interpretations of agroforestry. Indeed, this trend continues even now, albeit sparingly.

The inaugural issue of *Agroforestry Systems* (Vol. 1, No. 1, pp. 7–12; 1982) contained an editorial "What is Agroforestry?" It contained a selection on "definitions" of agroforestry, proposed by various authors. Summarizing those definitions, Björn Lundgren of ICRAF stated: **"***There is a frequent mixing up of definitions, aims, and potentials of agroforestry. It is, for example, rather presumptuous to define agroforestry as a successful form of land use which achieves increased production and ecological stability. We may indeed aim for these, and in many ecological and socioeconomic settings, agroforestry approaches have a higher potential to achieve these than most other approaches to land use. But, with the wrong choice of species combinations, management practices, and lack of peoples' motivation and understanding, agroforestry may indeed fail just like any other form of land use may fail, and it will still be agroforestry in the objective sense of the word.*" Furthermore, he said:

> "*A proper definition of agroforestry should stress two characteristics common to all forms of agroforestry and separate them from the other forms of land use, namely:*
> - *the deliberate growing of woody perennials on the same unit of land as agricultural crops and/or animals, either in some form of spatial mixture or sequence;*
> - *there must be a significant interaction (positive and/or negative) between the woody and non-woody components of the system, either ecological and/or economical.*
>
> *"When promoting agroforestry, one should then stress the potential of it to achieve certain aims, not only by making theoretical and qualitative remarks about the benefits of trees but also, and more importantly, by providing quantitative information."* (Lundgren 1982).

These ideas were later refined through in-house discussions at ICRAF, and the following definition of agroforestry was suggested:

> "*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economical interactions between the different components.*" (Lundgren and Raintree 1982).

This definition implies that:

- agroforestry normally involves two or more species of plants (or plants and animals), at least one of which is a woody perennial
- an agroforestry system always has two or more outputs

- the cycle of an agroforestry system is always more than one year
- even the simplest agroforestry system is more complex, ecologically (structurally and functionally) and economically, than a monocropping system.

Though not "perfect" in all respects, the above definition was increasingly used in ICRAF publications and thus achieved wide acceptability. Now (2020), ICRAF's website (www.icraf.org) proclaims a three-word-definition of agroforestry: "agriculture with trees." Recognizing perhaps that such an abstract definition may not be well received, the website further explains "Agroforestry is the interaction of agriculture and trees, including the agricultural use of trees. This includes trees on farms and in agricultural landscapes, farming in forests and along forest margins, and tree-crop production, including cocoa, coffee, rubber, and oil palm. Interactions between trees and other components of agriculture may be important at a range of scales . . ."

2.3 Definitions Galore

During the early part of the development of agroforestry (the 1980s), a considerable amount of time used to be spent in any group discussion or conference, in which agroforestry used to be on the agenda, on discussing "what is agroforestry." Participants would passionately and sometimes animatedly discuss and even throw barbs at each other to articulate their points of view – and lack thereof – on what agroforestry is or is not or ought to be. Most writings and opinions invariably contained the authors' description and perceptions of agroforestry, which sometimes would run into several paragraphs. Numerous definitions of agroforestry have thus been proposed; some of these are presented in Table 2.1. A closer look at these definitions shows that the various definitions are not definitions in strictly scientific terms but mostly reflections of characteristics and expectations from agroforestry for specific countries and regions. Over the years, agroforestry became a well-established term in land-use parlance such that definitions of the term can be found in most of the common dictionaries and encyclopedias. A sampling of some such entries is listed in Table 2.2. So much so, the surge of enthusiasm for defining agroforestry has subsided.

2.4 Concepts, Principles, and Attributes of Agroforestry

Agroforestry is now widely accepted as an approach to land use involving a deliberate mixture of trees with crops and/or animals. The lack of a universally accepted definition does not limit its role and potential in land management. Indeed, even the long-established land-use disciplines such as agriculture and forestry do not have completely satisfactory definitions, and a universally acceptable definition has not been a prerequisite for the development of those disciplines.

As depicted in Figure 2.1, agroforestry is an interface between agriculture and forestry and encompasses mixed land-use practices. These practices have been developed primarily in response to the special needs and conditions of tropical developing countries that have not been satisfactorily addressed by advances in conventional agriculture or forestry. In the tropics, the term is used to denote practices ranging from simple forms of shifting cultivation to complex hedgerow intercropping systems; systems including varying densities of tree stands to the high-density multistoried homegardens of the humid tropics; and systems in which trees play a predominantly service role (e.g., windbreaks) to those in which they provide the main commercial product (e.g., intercropping with shaded perennial plantation crops) (Nair 1989). In the temperate (industrialized) nations, agroforestry is practiced primarily for exploiting the biological interactions between trees and crops for a variety of environmental benefits through practices such as riparian buffer, windbreak, silvopasture, alley cropping, and other forms of intercropping, and forest farming (Chapter 10).

Table 2.1 Some Global Definitions of Agroforestry[§]

Region	Definition	Source
Global, Tropics	Purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit.	Nair (1993)
Global, Tropics	A dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in agricultural landscape, diversifies and sustains smallholder production for increased social, economic, and environmental benefits.	Garrity (2004); ICRAF (2008)
Tropical, Global	A form of multiple cropping under which three fundamental conditions are met: 1. There exist at least two plant species that interact biologically; 2. At least one of the plant species is a woody species; and 3. At least one of the plant species is managed for forage, annual or perennial crop production.	Somarriba (1992)
North America (USA and Canada)	Intensive land-use management that optimizes the benefits (physical, biological, ecological, social) from biophysical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock	Garrett (2009); AFTA[†]
	The intentional integration of trees and shrubs into crop and animal production systems.	Schoeneberger et al. (2017)
Canada	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 to obtain economic, ecological, environmental and cultural benefits.	Gordon and Newman (1997)
France	The cultivation of the soil with a simultaneous or sequential association of trees and crops or animals to obtain products or services useful to man.	Torquebiau (2000)
Europe	Agroforestry or agro-silviculture/agro-sylviculture is a land use management system in which trees or shrubs are grown around or among crops or pastureland. It combines shrubs and trees in agricultural and forestry technologies to create more diverse, productive, profitable, healthy, and sustainable land-use systems.	EURAF[‡](www.eurafagroforestry.eu)
Europe	The practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions.	AGFORWARD (2016) Burgess et al. (2015)
Australia	A term used to describe commercial tree growing activities as timber belts, wide-spaced plantations, or as conventional plantations which are carefully integrated into a farm or catchment for land- and water-care benefits, improved productivity and profitability of the farm and the region and to help provide income for retirement and farm succession.	Washusen and Reid (1996)

[†]AFTA = Association for Temperate Agroforestry (http://www.aftaweb.org)
[‡]EURAF = European Agroforestry Federation (www.eurafagroforestry.eu)
AGFORWARD: A large, European-Commission-funded agroforestry project with the participation of 15 countries of Europe, 2014 – 2017; coordinator: PJ Burgess.
[§]Modified from Garrett (2009)

Today, agroforestry represents the modern, science-based approach to harnessing the sustainability attributes and production benefits of time-tested practices of integrating trees in agricultural systems for a variety of objectives. Its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use is receiving increasing attention in development programs around the world. The basic concept that is common to all diverse agroforestry practices is the **purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit.** This is the essence of agroforestry.

In addition to the above, three fundamental attributes are common to all agroforestry practices:

Table 2.2 Some Dictionary Definitions of Agroforestry

Encyclopedia Britannica
Agroforestry, cultivation and use of trees and shrubs with crops and livestock in agricultural systems.
Wikipedia
Agroforestry is a land-use management system in which trees or shrubs are grown around or among crops or pastureland. This intentional combination of agriculture and forestry has varied benefits, including increased biodiversity and reduced erosion. **(USDA National Agroforestry Center).**
The Free Dictionary
A system of land use in which harvestable trees or shrubs are grown among or around crops or on pastureland, as a means of preserving or enhancing the productivity of the land.
Merriam Webster Dictionary
Land management involving the growing of trees in association with food crops or pastures.

Productivity: A mixture of plant species is capable of "over-yielding" as proposed by De Wit (1960) and producing more than the combined production of the respective monocultures. Although competitive interactions can potentially depress yields of mixtures, the beneficial effects of species mixtures could be substantial because of better resource exploitation than in single-species systems, beneficial interactions where one species benefits another, and reduced pest- and disease incidence in mixtures relative to monocultures. Therefore, agroforestry systems, being mixtures of different life forms, could maintain or increase production (of preferred commodities) as well as productivity (of the land). Such productivity improvements can happen in different ways, including the increased output of tree products, improved yields of associated crops, reduced input requirements, increased labor efficiency, and increased resilience to climate change and other environmental vagaries.

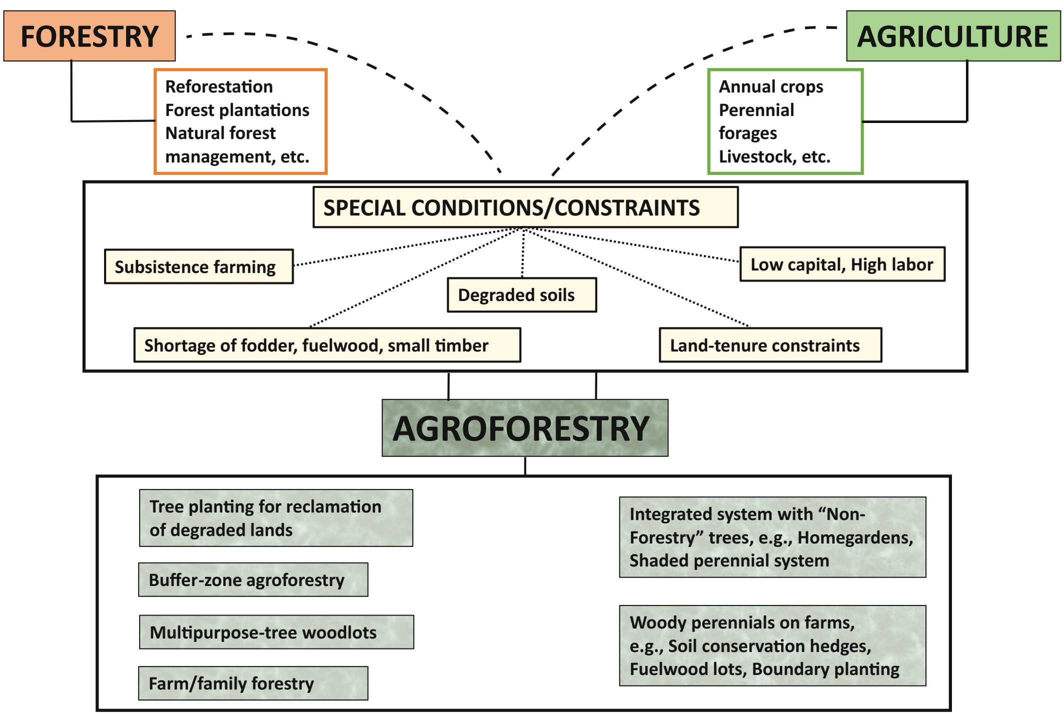

Figure 2.1 Agroforestry as an interface between agriculture and forestry. Source: Adapted from the first edition of the book (Nair 1993).

Sustainability: By conserving the production potential of the resource base, mainly through the beneficial effects of woody perennials on soils (see Section IV of this book), agroforestry can achieve and indefinitely maintain conservation and fertility goals.

Adoptability: The word "adopt" here means "accept," and it may be distinguished from another commonly-used word adapt, which implies "modify" or "change." The fact that agroforestry is a relatively new word for an old set of practices means that, in some cases, agroforestry has already been accepted by the farming community. However, the implication here is that improved or new agroforestry technologies that are introduced into other areas should also conform to local farming practices.

The Four "I" Words

Four "I" words have been proposed as the key criteria for characterizing agroforestry practices and distinguishing them from other land-use practices in the United States and Canada (Garrett 2009). These are:

Intentional: The key components of agroforestry systems (trees, crops, and/or animals) are intentionally designed, established, and managed together on the same land management unit for optimum benefits and services rather than as individual components being managed separately.

Intensive: Agroforestry practices are managed intensively for their productive and protective functions.

Integrated: The components are combined structurally and functionally into a single integrated unit; the integration could be horizontal or vertical and above- or below ground for better utilization of resources.

Interactive: Maximization of the benefits of biophysical interactions among components of the system to yield multiple products and services is a key trait of all agroforestry practices.

Garret (2009) has explained how these criteria could be used to distinguish agroforestry practices from other land-use practices in North America. For example, an intensively managed fruit- or nut tree plantation that is designed and managed to maximize the production of only one preferred product does not qualify as an agroforestry practice. On the other hand, if that enterprise is designed to allow the introduction of pasture and grazing animals under the trees, it becomes a silvopastoral (agroforestry) practice.

After the initial phase, agroforestry as a land management practice has undergone several paradigm shifts. Its early tag was a subsistence production system involving smallholders in the developing countries and the production of multiple products such as food, fuel, fodder, green manure, etc. on the same unit of land. Over the years, its scope and potential progressed to include intensively managed multi-strata production systems, and as a means to provide ecosystem services including climate change mitigation. Despite such transformations, multifunctionality and ecosystem resilience remain the central features of this integrated land-use system.

2.5 Other Agroforestry-Related Land-Use Systems

The last two-to-three decades of the 20th century witnessed an escalating worldwide interest in tree planting activities as described in Chapter 1 (Figure 1.4). This resulted in the emergence and popularization of several other terms with "forestry" endings. Notable among these were *Community Forestry, Farm Forestry,* and *Social Forestry.* Later, several other similar terms, such as Urban (and Peri-Urban) Forestry, Food Forest, and Permaculture emerged (see Chapter 11, Section 11.5), and more are – could be – expected. Although these terms have also been not defined precisely, it is generally accepted that they all emphasize the recognition of the role and importance of trees in the landscape and the self-help aspect – people's participation – in tree planting activities. Some of these activities may not necessarily be in association with agricultural crops and/or animals as in agroforestry but have social objectives ranking equally in importance with production objectives. Thus, social forestry is considered as the practice of using trees and/or tree planting specifically to pursue social objectives, usually betterment of the poor, through the delivery of the benefits (of trees and/or tree planting) to the local people; it is sometimes described as "tree growing by the people, for the people." Community forestry, a form of social forestry, refers to tree planting activities undertaken by a community on communal lands, or the so-called common lands; it is based on the local people's direct participation in the process, either by growing trees themselves or by processing the tree products locally. Though claimed to be suited for areas with abundant common lands, the success of community forestry has been hampered by the "tragedy of the commons" (Hardin 1968). Farm forestry, a term commonly used mainly in Asia, indicates tree planting on farms. Urban Forestry, as the term indicates, refers to increased tree planting activities in urban areas primarily for aesthetic, environmental, and recreational purposes; but in situations, as in urban centers such as megacities of developing countries, some urban forestry initiatives are designed with food production objectives (the so-called Urban Food Forests). Permaculture, a term coined by Mollison and Holmgren (1981) refers to the intentional design and maintenance of agriculturally productive ecosystems, which feature the diversity, stability, and resilience of natural ecosystems (Mollison 1991).

The major distinction between agroforestry and these other terms and the practices they represent seems to be that agroforestry emphasizes the interactive association between woody perennials (trees and shrubs) and agricultural crops and/or animals for multiple products and services; the other terms refer primarily to tree planting, often as woodlots. As several authors have pointed out (e.g., Dove 1992; Laarman and Sedjo 1992), all these labels directly or indirectly refer to growing and using trees to provide food, fuel, medicines, fodder, building materials, recreational and environmental benefits, and cash income. Only blurred lines, if any, separate them and they all encompass agroforestry concepts and technologies. And, many of these terms are often used synonymously, and sometimes even out of context, in land-use parlance.

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Classification of Agroforestry Systems 3

Contents

Abstract

The main purpose of a classification scheme is to provide a practical framework for the synthesis and analysis of the information about existing agroforestry systems (AFS) and the development of new and promising ones. During the early stages of AF development in the tropics, a substantial database was generated from a global inventory of tropical AFS. Using that database, a classification scheme was developed based on the system's structure (nature and arrangement of components) as the primary criterion, and three major categories of AFS were identified: agrisilvicultural, silvopastoral, and agrosilvopastoral systems. Other criteria such as the system's function (major role or output), ecological distribution (rainfall, elevation), and socioeconomic characteristics (subsistence, commercial) were then used to group the systems in a purpose-oriented manner: for example, a silvopastoral system in tropical savannas, an agrisilvicultural system for soil conservation, and so on. In situations where such a detailed classification is not relevant or needed as in the

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_3

temperate regions, classification has been limited to the identification of the major practices. Thus, during the late 1990s to early 2000s, alley cropping, silvopasture, forest farming, riparian buffer, and windbreaks were recognized as the major agroforestry practices in North America. Almost identical terms with slight modifications were adopted to designate the AF practices in Europe too. These terms have subsequently been modified and expanded in both North America and Europe.

3.1 Introduction

If we look at the existing land-use systems using the broad definition and concepts of agroforestry given in Chapter 2, we find that various types of agroforestry combinations abound in all ecological and geographical regions of the world, but most distinctively in the tropics. Several descriptions of promising land-use systems involving integrated production of trees and crops, as well as innovative scientific initiatives aimed at improving such systems, have been reported without the label of "agroforestry" before the arrival and acceptance of such a new word. To understand and evaluate the existing agroforestry systems and to develop action plans for their improvement, it is necessary to classify them according to some common criteria.

The main purpose of classification should be to provide a practical framework for the synthesis and analysis of information about existing systems and the development of new and promising ones. Besides, a classification scheme will aid in the transfer and application of knowledge gained from one location to another. Depending on the focus and emphasis of strategies for the development of improved systems, the nature of a given framework will vary. Therefore, any classification scheme should:

- Include a logical way of grouping the major factors on which production of the system will depend
- Indicate how the system is managed (pointing out possibilities for management interventions to improve the system's efficiency)
- Offer flexibility in re-grouping the information, and
- Be easily understood and readily handled.

The complexities of these requirements suggest that a single classification scheme may not satisfactorily accommodate all of them; perhaps a series of classifications will be needed, with each one based on a definite criterion to serve a different purpose.

3.2 Early Efforts in Classification

In the early stages of agroforestry development, several attempts were made to classify agroforestry systems (AFS). These were mostly focused on concept development rather than on evaluation and data-based analysis of the systems. While some of them were based on only one criterion such as the role of components (King 1979) or temporal arrangement of components, others tried to integrate several of these criteria in hierarchical schemes in rather simple ways (Torres 1983) or more complex ones (Combe and Budowski 1979; Huxley 1983). The most organized effort in understanding the systems has been a global inventory of agroforestry systems and practices in developing countries undertaken by ICRAF between 1982 and 1987. That activity involved systematically collecting, collating, and evaluating data on numerous such land-use systems around the world (Nair 1987). It assembled, for the first time, a substantial body of information on AFS including their structures and functions, and their merits and weaknesses. As that activity progressed, it became increasingly clear that a classification scheme was necessary to compile and process the information that was being gathered. At the same time, the comprehensive and broad-based nature of the inventory provided a substantial database for developing a widely-applicable classification scheme. That scheme was based on the notion that the most obvious and easy-to-use criteria for classifying AFS systems would be the spatial and temporal arrangement of components, the importance and role of components, the production aims or outputs from the system, and the social and economic features. These attributes correspond to the systems' structure, function (output), socioeconomic nature, or ecological (environmental) spread, respectively, and represent the main purpose of a classification scheme. Thus, the following sets of criteria were adopted in the classification proposed by Nair (1985).

- ***Structural basis:*** refers to the nature of the components, including spatial arrangement of the woody component, vertical stratification of all the components, and temporal arrangement of the different components.
- ***Functional basis:*** refers to the major function or role of the system, usually furnished by the woody components. These can be of service- or protective nature as well, e.g., windbreak, shelterbelt, soil conservation, shade trees, and the like. Apart from these service benefits, the woody components also provide one or more direct forms of production such as logs for building construction, furniture making, peeler logs (e.g., plywood), chip or particleboard, round timber posts or poles, fuelwood, fodder, or green manure, fruits or nuts, besides the production of chemicals such as gums, resins, and dyes.
- ***Ecological basis:*** refers to the environmental condition and ecological suitability of systems, based on the assumption that certain types of systems can be more appropriate for certain ecological conditions; i.e., there can be separate sets of agroforestry systems for arid and semiarid lands, tropical highlands, lowland humid tropics, etc.
- ***Socioeconomic basis***: refers to the level of inputs of management (low input, high input) or intensity or scale of management and commercial goals (subsistence, commercial, intermediate).

While proposing this classification, the author emphasized that the broad foundations upon which it is based are by no means independent or mutually exclusive and that indeed they are interrelated. The structural and functional bases often relate to the biological nature of the woody components in the system, whereas the socioeconomic and ecological stratification refers to the organization of the systems according to those local conditions. It was further proposed that the complexity of agroforestry classification could be considerably reduced if the structural and functional aspects are taken as the primary considerations in the categorization of the systems and socioeconomic and agroecological/ environmental (as well as any other such physical or social) factors are taken as a basis for stratifying or grouping the systems for defined purposes (Table 3.1).

3.3 Classification Based on the Structure of the System

The structure of the system can be defined in terms of its components, their arrangement, and the expected role or function of each.

3.3.1 Nature of Components

In AFS, three basic sets of elements or components are managed by the land user, namely, the tree or woody perennial, the herb (agricultural crops including pasture species), and the animal. As we have seen in Chapter 2, for a land-use system to be designated as an AFS, it must have a woody perennial. In most AFS, the herbaceous species are also involved, the notable exceptions being apiculture and aquaculture with trees, and shaded perennials systems involving shade-tolerant woody perennials such as coffee, cacao, and tea under the shade trees. Animals are only present in some AFS. This leads to a simple classification of AFS as given below and depicted in Figure 3.1.

Agrisilviculture – crops (including shrubs/vines) and trees

Silvopastoral – pasture/animals and trees

Agrosilvopastoral – crops, pasture/animals, and trees

Table 3.1 Major agroforestry practices in the tropics.

Agroforestry practice	Brief description
Tropical agroforestry	
Alley cropping (hedgerow intercropping)	Fast-growing, preferably leguminous, woody species grown in crop fields; the woody species pruned periodically to a low height (<1.0 m) to reduce shading of crops; the prunings applied as mulch into the alleys as a source of organic matter and nutrients, or used as animal fodder.
Homegardens	Intimate multistorey combinations of a diverse and large number of trees and crops in homesteads; livestock may or may not be present.
Improved fallow	Fast-growing, preferably leguminous, woody species planted and left to grow for short periods (2–3 years) of fallow between cropping periods for soil fertility enhancement; woody species may yield economic products.
Multipurpose trees (MPTs) on farms and rangelands	Fruit trees and other MPTs scattered haphazardly or planted in some systematic arrangements in crop or animal production fields; trees provide products such as fruits, fuelwood, fodder, and timber.
Silvopasture: • Grazing systems • Cut and carry system (Protein banks)	Integration of trees in animal production systems: o Cattle grazing on pasture under widely spaced or scattered trees. o Stall-feeding of animals with high-quality fodder from trees grown in blocks on farms.
Shaded perennial-crop systems	Growing shade-tolerant species such as cacao and coffee under or in between overstorey shade-, timber-, or other commercial tree crops.
Shelterbelts and windbreaks	Use of trees to protect fields from wind damage, sea encroachment, floods, etc.
Taungya	Growing agricultural crops during the early stages of establishment of forestry (timber) plantations

Source: Nair (2012)

Figure 3.2 presents a more comprehensive scheme than Figure 3.1 showing classifications based on not only the nature of components but function (products and services) and geographical/ecological distribution of systems. As mentioned above, there are also a few other systems, such as multipurpose woodlots (that interact economically and ecologically with other land-use production components and hence fall under the purview of agroforestry definition), apiculture with trees, and integration of trees and shrubs with fish production (*aquasilviculture*?) that do not fall into these categories. In the absence of a better term to encompass these, they are grouped under "others."

This categorization of AFS into three major types is somewhat fundamental; one of these types can conveniently be used as a prefix to other terms emanating from other classification schemes to explicitly express the basic structure/composition of any system. For example, there can be an agrisilvicultural system for food production in the lowland humid tropics at a subsistence level of production, a commercial silvopastoral system for fodder and food production in lowland subhumid (or dry) tropics, an agrosilvopastoral system for food production and soil conservation in highland humid tropics, and so on. Therefore, it seems logical, compatible, and pragmatic to accept the components as the basic criterion in the hierarchy of agroforestry classification. The classification scheme developed by Nair (1985) was perhaps the first such effort based on a comprehensive database from the above-mentioned inventory of agroforestry systems in the tropics.

It may be noted that the term agrisilviculture (rather than agrosilviculture) is used to denote the combination of trees and crops, whereas agrosilvopastoral (rather than agrisilvipastoral) is used for crops + animals/pasture + trees. The intention here is to limit the use of the word agrisilviculture only to those combinations involving agricultural crops and trees. The word agrosilviculture can encompass all forms of agriculture (including animal husbandry) with trees and would thus be

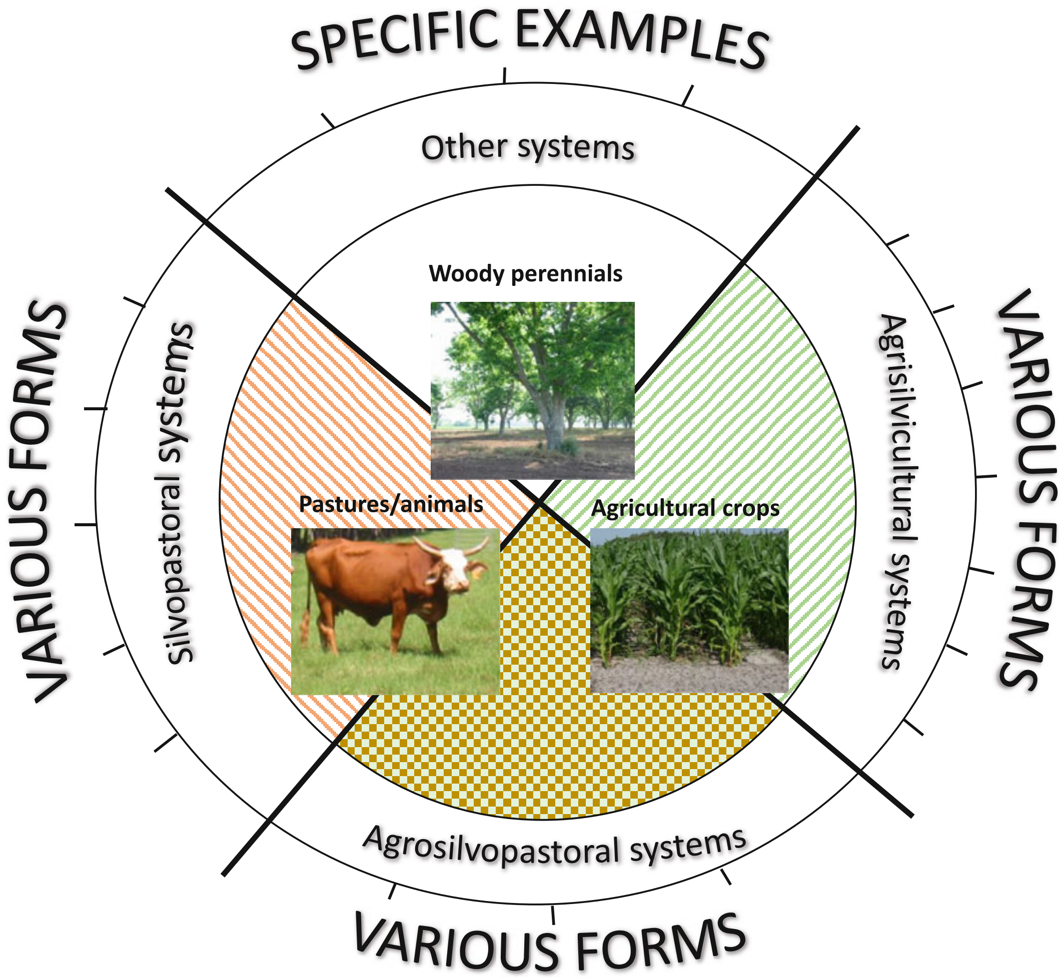

Figure 3.1 Classification of agroforestry systems based on the nature of components. Source: Nair (1993)

another word for agroforestry. That again is the reasoning behind the use of the all-inclusive "agro" prefix in agrosilvopastoral. During the process of evolution of the word agroforestry, there was an argument as noted in Chapter 2 that the proper nomenclature from the linguistic perspective for a term that combines agriculture and forestry should be "agriforestry" and not agroforestry. After all, several other usages can be found in technical languages that may not strictly satisfy the niceties of conventional linguistic usage.

3.3.2 Arrangement of Components

The arrangement of components refers to the plant components of the system (especially if the system involves plant and animal components). Such plant arrangements in multispecies combinations can involve the dimensions of space and time. Spatial arrangements of plants in agroforestry mixtures in the tropics vary from dense mixed stands (as in homegardens) to sparsely mixed stands (as in extensive silvopastoral grazing systems and extensive tree-intercropping

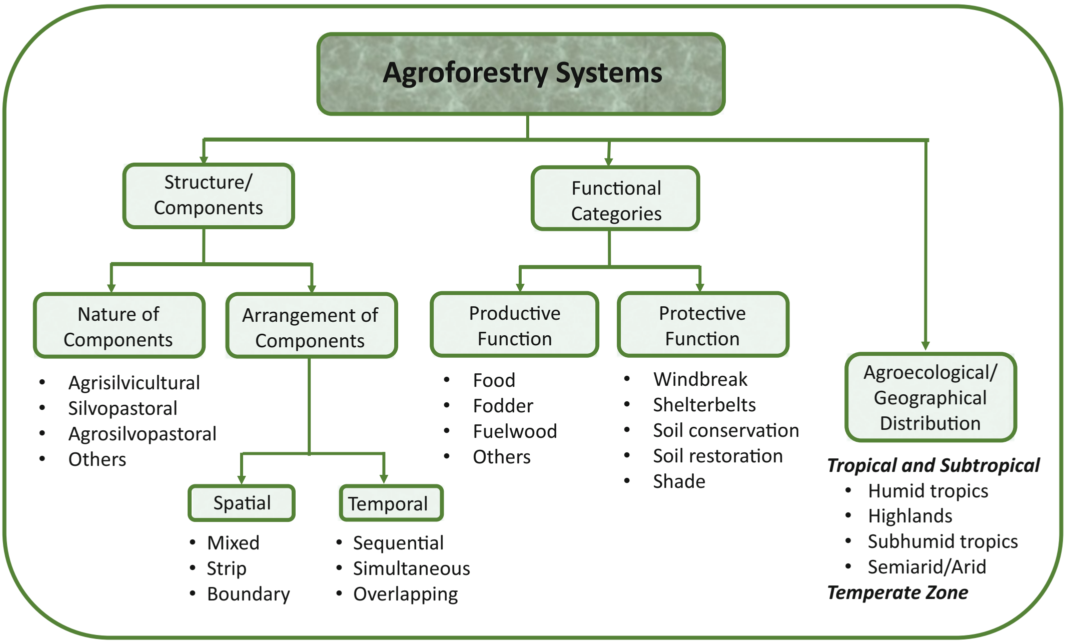

Figure 3.2 Classification of agroforestry systems based on the structure and function of components

systems such as the parkland systems: see Chapter 9, Section 9.4.1). Moreover, the species can be in zones or strips of varying widths in several scales of zones varying from microzonal (alternate rows) to macrozonal arrangements. A commonly mentioned example of the zonal pattern is hedgerow intercropping (alley cropping: Chapter 6). An extreme form of zonal planting is the boundary planting of trees on edges of plots and fields for a variety of purposes and outputs (fruits, fodder, fuelwood, fencing and protection, soil conservation, windbreak, and so on). It is also important to note that extreme forms of macrozonal arrangements can be construed as sole cropping systems; the extent of interactive association of different components, however, can be used as the criterion to decide the limits between macrozonal agroforestry and sole crop systems.

Temporal arrangements of plants in agroforestry can also take various forms. An extreme example is the conventional shifting cultivation cycles involving 2 to 4 years of cropping followed by more than 15 years of fallow when a selected woody species or a mixture of species is planted or allowed to regenerate naturally (see Chapter 5, Figure 5.2). Similarly, some silvopastoral systems may involve grass leys in rotation with woody species with the same species of grass remaining on the land for several years during the grass phase. These temporal arrangements of components in agroforestry have been described by terms such as coincident, concomitant, overlapping (of which the extreme case is relay cropping), sequential, interpolated, and so on a shown in Figure 3.3 (Huxley 1983; Kronick 1984; Nair 1993). The Coincident systems represent simultaneous crop combinations in which different crops occupy the land together. For example, tea/coffee + shade trees or pasture under trees. In a Concomitant system, different crop components occupy the land together for some period, e.g., *Taungya* (Chapter 5). Agroforestry systems, in which annual crops are grown under woody perennials may be described as Intermittent. In situations where different crops occupy the land at different times, as in homegardens, the temporal arrangement can be described as Interpolated. When the components occupy the land at different times, such systems may be

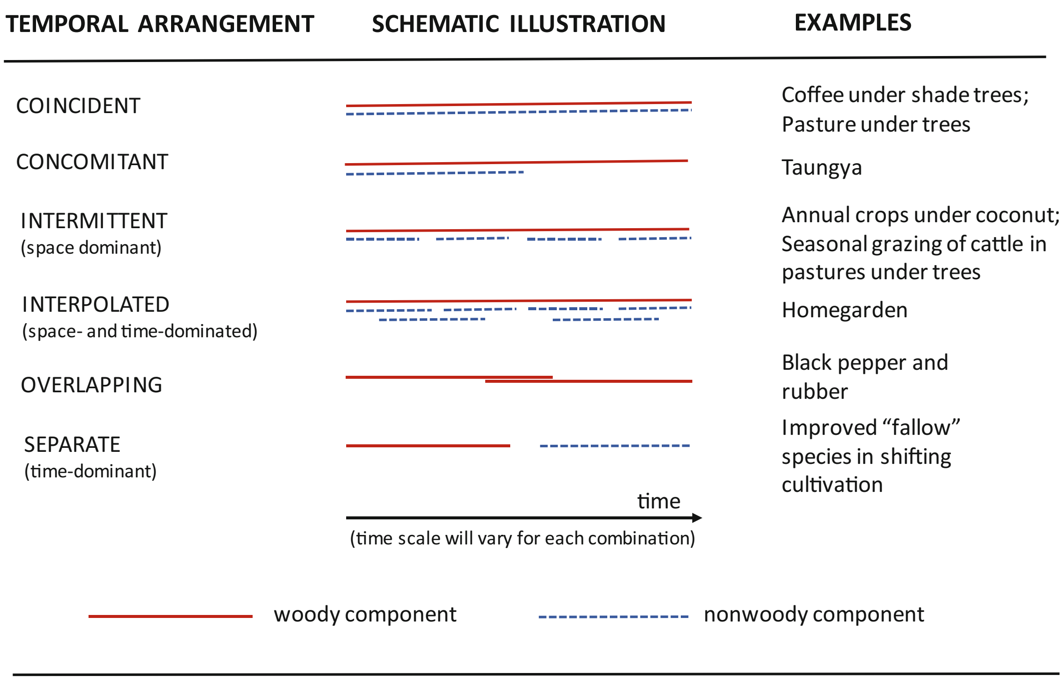

Figure 3.3 Temporal arrangements of woody and nonwoody components in agroforestry systems

classified as Sequential systems (e.g., improved fallows). Overlapping systems represent those in which two or more woody perennials occupy the land continuously, e.g., specialty spice trees (see Chapter 13, Section 13.4.1) interplanted with other usually taller trees such as coconut palms or timber species).

3.4 Based on the Function of the System

Production and conservation (which are the cornerstones of sustainability) are two fundamental attributes of all AFS as explained in Chapter 2. This implies that all AFS have a productive function yielding one or more products that usually meet basic needs, as well as a service role (i.e., protecting and maintaining the production systems). This approach recognizes the service roles of woody perennials as factors contributing to the production of one or more of these basic needs. For example, the soil conservation benefit of agroforestry practices can be expressed in terms of their contribution to augmenting the sustainability of crop production. Similarly, amelioration of microclimate through well-designed arrangements of trees and crops (e.g., shelterbelts) can be evaluated in terms of its effects on crop yields; however, the climate-change mitigation benefits of AFS, particularly through soil carbon sequestration is a long-term benefit (see Chapter 20), the value of which cannot be assessed in short-term studies.

The emphasis on the production of outputs should not diminish the importance of sustainability. Although production is a very important consideration, it is the sustainability attribute that makes AFS different from other approaches to land use. Moreover, all AFS produce more than one basic-need output (largely because of the multipurpose nature of the associated woody perennial component). Therefore, all AFS have both productive and protective roles, though to varying degrees. Depending on the relative dominance of a specific role, the system can be termed productive or protective. Production of a specific output should not, therefore, be used as the sole criterion for classifying AFS. The production of output, or for that matter any other aspect, may be chosen as a basis for undertaking an evaluation of available agroforestry options.

3.5 Based on Ecological Characteristics

During the late 1970s and early 1980s, several enumerations of agroforestry practices were presented from various geographical regions at seminars and workshops. Notable among them are the group discussions held at CATIE, in Turrialba, Costa Rica (de las Salas 1979); at ICRAF, in Nairobi (Buck 1981; Chandler and Spurgeon 1979; Huxley 1983); and at IITA, Ibadan, Nigeria (McDonald 1982). Several compilations on specific systems were also available such as the *Acacia (Faidherbia) albida* system in West Africa (Vandenbeldt 1992), and the *Prosopis cineraria* system in western India (Mann and Saxena 1980). Additionally, country- or regional overviews were undertaken, such as reviews of agroforestry in francophone Africa (FAO 1981a), the Indian subcontinent (FAO 1981b), and Latin America (Montagnini 1986; Padoch and de Jong 1987). Several other notable overviews have been published (Lundgren and Raintree 1982; Nair 1983b, 1983c, 1984). The Agroforestry System Description Series in *Agroforestry Systems*, which was a major output from ICRAF's Agroforestry Systems Inventory Project (Nair 1987), was the most coordinated effort in describing such existing systems.

Most of these AFS characterizations pertained to specific ecological conditions of different geographical regions in the tropics. It was thus easy to find several descriptions of AFS in, say, the highlands, subhumid tropics (or the tropical highlands, as they are popularly known): for example, the *Chagga* system on Mount Kilimanjaro in Tanzania (Fernandes et al. 1984), hill farming in western Nepal (Fonzen and Oberholzer 1984), multipurpose tree integration in the highlands of Rwanda (Neumann 1983), and casuarina and coffee system in Papua New Guinea (Bourke 1984). Recommendations on agroforestry practices had also been suggested for specific agroecological regions, for example, the hilly regions of Rwanda (Nair 1983a), and for areas with common physical features such as sloping lands (Young 1989) or soil constraints such as acidity (Benites 1990).

Descriptions of existing systems, as well as recommendations of potential agroforestry technologies for specific agroecological zones, include a mixture of various forms of agroforestry: there could be agrisilvicultural, silvopastoral, or agrosilvopastoral systems in any of the zones. For example, based on an analysis of the agroforestry potential for sloping lands in various parts of the world, Young (1989) reported that all three basic categories of agroforestry (agrisilvicultural, silvopastoral, and agrosilvopastoral) could be found in sloping lands.

Various system characterizations and descriptions such as agrisilvicultural systems for fuelwood production in semiarid lands, silvopastoral systems for animal production in sloping lands, multistrata homegardens in humid tropics, etc., are common in agroforestry literature. Moreover, descriptions of existing systems, as well as recommendations of potential agroforestry technologies for specific agroecological zones include a mixture of various forms of agroforestry in terms of the nature and arrangement of components, and several agroforestry systems can be found within the same ecological regions. Thus, in general, for any specific agroforestry practice, agroecological zonation alone cannot be taken as a satisfactory criterion for classification. Agroecological characteristics could, however, be used as a basis for designing agroforestry systems, because similar ecological regions can be found in different geographical regions and the agroforestry systems in similar ecological zones in different geographical regions are structurally (in terms of the nature of species components) similar. The bottom line is that several types of AFS are relevant to any major agroecological zone; the emphasis of the practice will also vary depending on the special conditions of a zone.

3.6 Based on Socioeconomic Criteria

Socioeconomic criteria such as the scale of production and level of technical input and management have also been used as a basis for classifying agroforestry systems. Three such categories have been proposed: commercial, intermediate, and subsistence. In general, they are characterized by low, medium, and high levels of technical input and management. Subsistence farmers consume most of what they produce (or, produce most of what they consume), whereas commercial farmers sell most – if not all – of what they produce on their farm or enterprise. The intermediate group comes in between these two categories. Most AFS practiced in various parts of the developing countries come under the subsistence category. Shifting cultivation, which is still prevalent in many parts of the tropics although not much talked about lately (see Chapter 5), is a common form of this category. All subsistence AFS, however, are not as resource-depleting as traditional shifting cultivation. For example, the integrated, multi-species homegarden system is an ecologically sound AFS (Wiersum 1980; Michon et al. 1986; Kumar and Nair 2006: Chapter 7). Similarly, reports on several sustainable systems of a subsistence nature from many other tropical regions can be found in the early literature of agroforestry, for example, from Latin America (Wilken 1977), arid West Africa (von Maydell 1979, 1987; Le Houerou 1987), humid West Africa (Getahun et al. 1982), and India (ICAR 1979).

Grouping agroforestry systems according to these socioeconomic and management criteria may offer a purpose-oriented action plan; however, there are some drawbacks too. The criteria for defining the various classes are not easily quantifiable; the standards set for such differentiation will reflect the general socioeconomic situation of a given locality. What is considered a "subsistence" system in one locale may well fall under the "intermediate" or even a higher category in another setting. Moreover, these class boundaries will also change with time. A good example is the gum-arabic production system of Sudan. It used to be a flourishing "intermediate" system consisting of a planned rotation of *Acacia senegal* tree for gum production for 7–12 years. The tree also provided fodder and fuelwood and improved soil fertility (Seif-el-Din 1981). But with the advent of artificial substitutes for gum arabic, the *Acacia senegal*/millet system has now degenerated into a shrinking, subsistence system. Therefore, socioeconomic factors that are likely to change with time and management conditions cannot be rigidly adopted as a satisfactory basis for an objective classification scheme, but they can be employed as a basis for grouping the systems for a defined objective or action plan.

3.7 Other Approaches to Classification of Tropical Agroforestry Systems

The component-based classification of AFS explained above (Figures 3.1, 3.2 and 3.3) have been used somewhat widely in tropical agroforestry literature. Over the years, however, the relevance and application to all different forms of AFS have been questioned. Torquebiau (2000) argued that the three broad categories (agrisilviculture, silvopasture, and agrosilvopasture) are either too vague or restrictive; he argued that agrisilviculture could almost be a synonym for agroforestry covering hundreds of practices, and the distinctions among the three categories could be faint when considering systems involving all three major components of crops, trees, and animals. Another weakness of that classification system is that it does not recognize that the components of a system could be arranged in time (sequentially or simultaneously) or space (mixed or zonal) patterns. Furthermore, that classification gives more emphasis to the tree component compared with the other components (crops or animals). Based on such considerations, some attempts at classifying agroforestry systems more robustly have since been reported. Torquebiau (2000) suggested a classification with six categories: crops under tree cover, agroforests, agroforestry in a linear arrangement, animal agroforestry, sequential agroforestry, and "minor" agroforestry techniques.

It has not, however, been established how this categorization would overcome some of the problems associated with the earlier classification scheme. Other classification schemes of agroforestry systems have also been proposed (e.g., Sinclair 1999); but, essentially, they all are based on the criteria and concepts described in Chapter 2. Various other terms are also used in agroforestry literature to refer to specific types of associations, notably in India where terms such as *silvi-pasture, agri-horti, horti-agri, silvi-horti, horti-silvi*, and so on, are found in local literature without a clear explanation of the basis for such categorizations. *Integrated Crop-Livestock-Forestry Systems* is a relatively new term that has sprung up, primarily in (or, for application in) Brazil (Bungenstab and Almeida 2014). The intent seems to be to make silvopasture as a "stand-alone" field distinct from the rest of the agroforestry applications (see Chapter 9, Section 9.6).

Tropical Agroforestry System Subgroups. To streamline the agroforestry systems nomenclature and reduce the number of major groups, Nair (2012, 2014) arranged the systems into five major subgroups based primarily on the nature of system components (multistrata systems, tree intercropping, silvopasture, protective systems, and agroforestry woodlots) with major types of agroforestry systems identified under some of them (Table 3.1; see also Chapter 4, Table 4.3). The total number of categories (nine) is still high – which also indicates how diverse agroforestry systems are.

3.8 Agroforestry Systems and Practices

The words "system" and "practice" are used commonly, and often synonymously, in agroforestry literature, adding to the confusion surrounding the classification of agroforestry. This is particularly so in the tropics, where agroforestry is more diverse, complex, and rooted in traditions and culture, than in the temperate regions. A distinction can be drawn between the two words system and practice: a *system* connotes the many parts, arrangements, and interactions created by integrating these parts, whereas *practice* is the customary, habitual, or expected procedure or way of doing something. Thus, an *agroforestry practice* denotes a distinctive arrangement of components in space and time and the actual application or use of an idea, belief, or method. An *agroforestry system* is a specific local example of a practice, characterized by environment, plant species and their arrangement, management, and socioeconomic functioning. Although hundreds of agroforestry systems have been recorded in the tropics, they all consist of a few (less than 20) distinct agroforestry practices. In other words, the same or similar practices are found in various systems in different situations. Table 3.2 lists the most common agroforestry practices that constitute the diverse agroforestry systems throughout the tropics and their main characteristics. It may be noted that both the systems and the practices are known by similar names, but the systems are (or ought to be) related to the specific locality or the region where they exist, or other descriptive characteristics that are specific to it. Nevertheless, the distinction between systems and practices is vague, and even not very critical for understanding and improving them; therefore, the words are used synonymously in agroforestry, as they are in other forms of land use too. As explained in the following section, however, the use of the word *practice* rather than *system* is better established in North America (the USA and Canada) and Europe, where agroforestry systems and practices are relatively few and are based on agricultural traditions.

Another term that is also frequently used is *agroforestry technology*. It refers to innovation or improvement, usually through scientific intervention, to either modify an existing system or practice or develop a new one. Such technologies are often distinctly different from the existing systems/practices; so, they can easily be distinguished and characterized.

Table 3.2 Major tropical agroforestry practices

Agroforestry Practice	Brief description (of arrangement of components)	Major groups of components	Agro-ecological adaptability
Agrisilvicultural systems (crops-including shrub/vine/tree crops – and trees)			
(1) Improved fallow	Woody species planted and left to grow during the fallow phase	w: fast-growing preferably leguminous h: common agricultural crops	In shifting cultivation areas
(2) Taungya	Combined stand of woody and agricultural species during early stages of establishment of plantations	w: usually plantation forestry spp. h: common agricultural crops	All ecological regions (where taungya is practiced); several improvements possible
(3) Alley cropping (hedge-row intercropping)	Woody species in hedges; agricultural species in alleys in between hedges; microzonal or strip arrangement	w: fast-growing, leguminous, that coppice vigorously h: common agricultural crops	Subhumid to humid areas with high human population pressure and fragile (productive but easily degradable) soils
(4) Multilayer tree gardens	Multispecies, multilayer dense plant associations with no organized planting arrangements	w: different woody components of varying form and growth habits h: usually absent; shade tolerant ones some-times present	Areas with fertile soils, good availability of labor and high human population pressure
(5) Multipurpose trees on crop lands	Trees scattered haphazardly or according to some systematic patterns on bunds, terraces or plot/field boundaries	w: multipurpose trees and other fruit trees h: common agricultural crops	In all ecological regions esp. in subsistence farming; also commonly integrated with animals
(6) Plantation crop combinations	(i) Integrated multistorey (mixed,dense) mixtures of plantation crops (ii) Mixtures of plantation crops in alternate or other regular arrangement (iii) Shade trees for plantation crops; shade trees scattered (iv) Intercropping with agricultural crops	w: plantation crops like coffee, cacao, coco- nut, etc. and fruit trees, esp. in (i); fuel-wood/fodder spp., esp. in (iii) h: usually present in (iv), and to some ex- tent in (i); shade-tolerant species	In humid lowlands or tropical humid/sui>- humid highlands (depending on the plantation crops concerned); usually in small- holder subsistence system
(7) Homegardens	Intimate, multistorey combination of various trees and crops around homesteads	w: fruit trees predominate; also other woody species, vines. etc. h: shade tolerant agricultural species	In all ecological regions, esp. in areas of high population density
(8) Trees in soil conservation and reclamation	Trees on bunds. terraces, raisers, etc. with or without grass strips; trees for soil reclamation	w: multipurpose and/or fruit trees h: common agricultural species	In sloping areas, esp. in highlands, reclamation of degraded. acid, alkali soils, and sand-dune stabilization
(9) Shelterbelts and wind breaks, live hedges	Trees around farmland/plots	w: combination of tall-growing spreading types h: agricultural crops of the locality	In wind-prone areas
(10) Fuelwood production	Interplanting firewood species on or around agricultural lands	w: firewood species h: agricultural crops of the locality	In all ecological regions

(continued)

Table 3.2 (continued)

Agroforestry Practice	Brief description (of arrangement of components)	Major groups of components	Agro-ecological adaptability
Silvopastoral systems (trees+pasture and/or animals)			
(11) Trees on rangeland or pastures	Trees scattered irregularly or arranged ac- cording to some systematic pattern	w: multipurpose; of fodder value f: present a: present	Extensive grazing areas
(12) Protein banks	Production of protein-rich tree fodder on farm/ rangelands for cut-and-carry fodder production	w: leguminous fodder trees h: present f: present	Usually in areas with high person: land ratio
(13) Plantation crops with pastures and animals	Example: cattle under coconuts in southeast Asia and the South Pacific	w: plantation crops f: present a: present	In areas with less pressure on plantation crop lands
Agrosilvopastoral systems (trees+ crops+ pasture/animals)			
(14) Homegardens involving animals	Intimate, multistorey combination of various trees and crops, and animals around homesteads	w: fruit trees predominate: also other woody species a: present	In all ecological regions with high density of human population
(15) Multipurpose woody hedgerows	Woody hedges for browse, mulch, green manure, soil conservation, etc.	w: fast-growing and coppicing fodder shrubs and trees h: (similar to alley cropping and soil conservation)	Humid to subhumid areas with hilly and sloping terrain
(16) Apiculture with trees	Trees for honey production	w: honey producing (other components may be present)	Depending on the feasibility of apiculture may be present)
(17) Aquaforestry	Trees lining fish ponds, tree leaves being used as 'forage' for fish	w: trees and shrubs preferred by fish (other components may be present)	Lowlands
(18) Multipurpose woodlots	For various purposes (wood, fodder, soil protection, soil reclamation, etc.	w: multipurpose species; special location specific species (other components may be present)	Various

Note: w = woody; h = herbaceous; f = fodder for grazing; a = animals

3.9 Classification of Agroforestry Practices in the Temperate Regions

Agroforestry practices and systems in the temperate zone are less diverse and complex compared to those in the tropics. Gold and Garrett (2009) have perceived agroforestry in the United States and Canada as based on agricultural traditions, in which an agricultural production system is an aggregation of various practices. This perception led to the development of a definition of agroforestry in the context of the USA and Canada (Chapter 2: Table 2.1), and recognition of five distinct North American agroforestry practices. Following considerable deliberations, the definition and the set of practices were adopted by the Association for Temperate Agroforestry (AFTA). The five practices are: alley cropping, forest farming, silvopasture, riparian buffer, and windbreaks (Table 3.3); experiences and advances in the application of the practices are summarized in Chapter 10. In addition to these five agroforestry practices, *Urban Food*

Table 3.3 Agroforestry practices in North America (USA and Canada)

Agroforestry Practices in North America

Alley cropping	Trees planted in single or grouped rows with crops in the wide alleys between the tree rows
Forest farming	Producing specialty crops for medicinal, ornamental, or culinary uses in forested areas
Riparian buffer strips	Strips of perennial vegetation (tree/shrub/grass) planted between croplands/pastures and streams, lakes, wetlands, ponds, etc.
Silvopasture	Combining trees with forage (pasture or hay) and livestock production
Windbreaks	Row trees around farms and fields, managed as part of crop or livestock operation to protect crops, animals, and soil from wind hazards

Source: AFTA (Association for Temperate Agroforestry), www.aftaweb.org (accessed 12 Feb 2019)

Forests (UFF) is now being recognized as a sixth addition to the N. American AF practices (Jose 2019): see Chapter 10, Section 10.3.5. In Europe too, where agroforestry efforts have gathered considerable momentum since the early 2000s, the North American model has been adopted by identifying distinct agroforestry practices instead of following any detailed classification of systems. The European Agroforestry Federation (EURAF) too has recognized five agroforestry practices that are comparable to the North American pattern: alley cropping, silvopasture, silvoarable, riparian buffer, homegardens or kitchen gardens, and forest farming (Table 3.4). The practices are described in Chapter 10. Figure 3.4, originally proposed by den Herder et al. (2015) for Europe and modified by Bentrup et al. (2017) for adaptation to the US and Canada, is a schematic presentation of agroforestry as a continuum among trees, crops, and livestock within the land management unit (field or pasture) in the temperate regions.

3.10 Concluding remarks: A Framework for Classification of Agroforestry Systems

The foregoing analysis shows that there is no universally applicable or acceptable scheme for the classification of agroforestry systems. Several models and schemes have been suggested, each of them usually for specific situations; therefore, each has limitations too for universal applicability. It

Table 3.4 Spatial agroforestry practices in Europe (Modified from Association for Temperate Agroforestry (AFTA 1997; Alavapati and Nair 2001; Nair 1994, Alavapati et al. 2004; Mosquera-Losada et al. 2009)

Agroforestry practice	Description	
Silvopasture		Combining woody with forage and animal production. It comprises forest or woodland grazing and pastoral land with hedgerows, isolated/scattered trees or trees in lines or belts
Homegardens or kitchen gardens		Combining trees/shrubs with vegetable production in urban areas, also known as part of "trees outside the forest"
Riparian buffer strips		Strips of perennial vegetation (trees/shrubs) natural or planted between croplands/pastures and water sources such as streams, lakes, wetlands, and ponds to protect water quality. They can be combined with arable lands (silvoarable) or grasslands (silvopasture) but are signified by its role in preserving water streams
Silvoarable		Widely spaced woody vegetation inter-cropped with annual or perennial crops. Also known as alley cropping. Trees/shrubs can be distributed following an alley cropping, isolated/scattered trees, hedges and line belts design
Forest farming		Forested areas used for production or harvest of natural standing specialty crops for medicinal, ornamental or culinary uses, including those integrating forest and agricultural lands

seems that John Saxe's famous description of "six blind men describing an elephant" (described in Chapter 1, Section 1.4.1) that has been used to express the uncertainties in characterizing global forestry can very well be applied to agroforestry too.

The complexity of the problem can be reduced if the structural and functional aspects of the system are taken as the criteria for categorizing the systems. Since there are only three basic sets of components that are managed by the land user in all agroforestry systems (woody perennials, herbaceous plants, and animals), a logical first step in classifying agroforestry should be based on the structure (nature and arrangement) of these components. As discussed previously, there are three major categories: agri-silvicultural, silvopastoral, and agrosilvopastoral. Having done such a preliminary categorization, the system can be grouped according to any of the purpose-oriented criteria mentioned above. Each

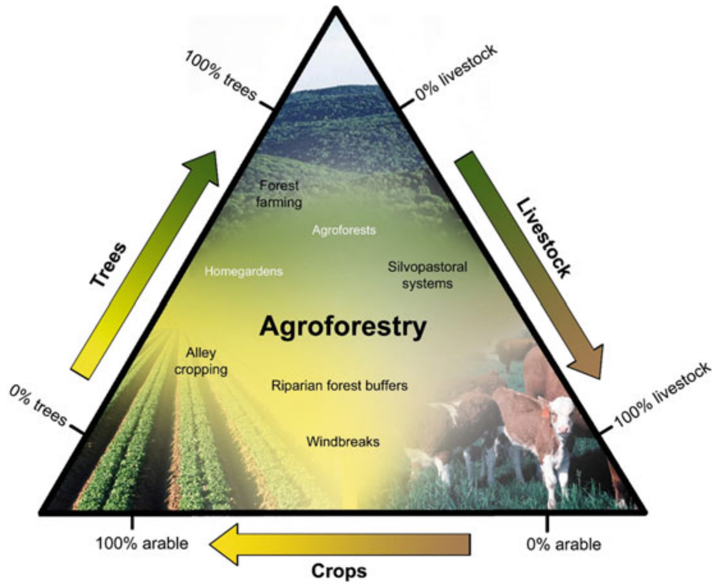

Figure 3.4 Agroforestry landscape continuum in North America Agroforestry represents a fluid continuum among trees, crops, and livestock, ranging from a few trees established with a field or pasture to multistory forests managed for a variety of products and services. Source: USDA/National Agroforestry Center

of the resulting groups can have any one of the above three categories as a prefix, for example, a silvopastoral system for cattle production in tropical savannas; and agrisilvicultural systems for soil conservation and food production in tropical highlands. Such an approach seems a logical, simple, pragmatic, and purpose-oriented way to classify agroforestry systems. In situations where such a detailed classification is not relevant or needed as in the temperate regions, classification could be limited to the identification of the major practices.

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4 Global Distribution of Agroforestry Systems

Contents

Abstract

In land-use parlance, the terms tropical and temperate are used loosely as approximate synonyms for *developing countries* and industrialized regions, respectively. From the agroforestry perspective, the arid and semiarid lands, and the subhumid and humid lowlands and highlands recognized in the FAO reports are considered as tropical developing regions and the temperate and Mediterranean regions as industrialized. The types of agroforestry systems (AFS) in these two major regions are different because of their climatic and socioeconomic characteristics. The common systems in the humid and subhumid tropics include forms of shifting cultivation and tree intercropping, homegardens, and shaded perennial associations, whereas various forms of silvopastoral systems, extensive tree intercropping, and windbreaks dominate the agroforestry scene in the semiarid and arid tropics. The major AF practices in the temperate regions include alley cropping, forest farming, silvopasture, riparian buffer, and windbreaks. While a substantial knowledge base and steady markets are available for tree species used in temperate agroforestry, most of the trees and other species used in tropical AFS are underexploited and of unknown nature. The global area under AFS is estimated

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as 1.6 billion hectares, with roughly 78% in the tropics and 22% in the temperate regions; but these are guestimates considering the lack of proper procedures for delineating the extent of areas under irregular stands of trees mixed with understory crops.

4.1 Introduction

Historically, agroforestry was popular in most parts of the tropics. More recently it has also become recognized as a sustainable and promising land-use strategy everywhere including the temperate regions of the world. Geographically, the tropics are located between 23.5 degrees north and south of the Equator, and the temperate region is between the Tropic of Capricorn and the Antarctic Circle in the Southern Hemisphere and between the Tropic of Cancer and the Arctic Circle in the Northern Hemisphere. These geographical definitions, however, are of limited value in discussions on land use; the terms tropical and temperate are used rather loosely and imprecisely while referring to vast areas between the two major zones extending over several degrees of latitude. In this book, the word tropics is used in a general sense to include not only countries and regions within the geographical limits of the tropics but also the subtropical developing countries that have agroecological and socioeconomic characteristics and land-use problems that are comparable to those of the countries within the tropical (geographic) limits. In other words, the word is used, even if erroneously, as a synonym for developing countries. This logic is also used when discussing agroforestry systems in the temperate zone in this chapter and elsewhere in this book (e.g., Chapter 10). The global distribution of the major ecosystems of the world is presented in Figure 12.4 (Chapter 12).

4.2 The Tropical Environment

Readers of this book are expected to have a general understanding of the physical, biological, and socioeconomic characteristics of the tropics; detailed discussions on those topics are not included here. Some discussion on the soils, however, is included in Chapter 15. For other details, readers may refer to other relevant books and publications, several of which are available. The current situation on the world environment and resources is updated continuingly on online sources; for example, https://www.globalforestwatch.org/dashboards/global?category=forest-change&treeLossTsc=eyJoaWdobGlnaHRlZCI6ZmFsc2V9 is a website that gives updated information on the extent of deforestation in different regions of the world.

The major climatic parameters that determine the environment of a location in the tropics are rainfall (quantity and distribution) and temperature regimes. Altitude is important because of its influence not only on temperature but also on land relief characteristics. Wikipedia defines a tropical climate in the Köppen climate classification as a non-arid climate in which all twelve months have mean temperatures of warmer than 18 °C (64 °F). In tropical climates, there are often only two seasons: wet and dry. Tropical climates are frost-free, and changes in the solar angle are small; the temperature remains relatively constant (hot) throughout the year, and the sunlight is intense. From the agroforestry point of view, the major ecological regions recognized in the FAO State of Food and Agriculture Reports (SOFA: www.fao.org/publications/sofa) are relevant: these are temperate, Mediterranean, arid and semiarid, subhumid tropical (lowland), humid tropical (lowland) and highland. These classes, excepting the first (and possibly the second), represent the tropical and subtropical lands where agroforestry systems exist or have potential. The main characteristics of these ecological regions (humid and subhumid lowlands, dry – semiarid and arid – regions, and highlands) are summarized in Table 4.1.

A special feature of the tropics that is not necessarily a direct consequence of its climate and ecology is the relatively poor economic, social, and developmental status over most of the region. As mentioned earlier, the word tropics is used synonymously with developing

Table 4.1 Main characteristics of the major ecological regions of agroforestry importance in the tropics and subtropics

Characteristics	Humid/subhumid lowlands	Dry regions (semiarid and arid)	Highlands
Climate	Hot, humid for all or most of the year, rainfall > 1000 mm; sometimes one or more extended dry periods per year; Koppen Af, Am and some Aw, esp. Aw”	Hot, one or two wet seasons and at least one long dry period; rainfall 1000 mm; Koppen Aw” (some), Aw’, and B climates	Cool temperatures, subhumid or humid (arid highlands are of low AF potential); altitude over 1000 m; Koeppen Ca, Cw (agricultural growing period over 120 days)
Vegetation and soils	Evergreen or semi-evergreen vegetation; Ultisols (Acrisols) and Oxisols (Ferralsols) and other acid, low-base tropical soils	Savannas with low or medium-high trees and bushes (Aw); thorn scrub and steppe grasslands (BS), Vertisols, Alfisols (Luvisols, Nitosols) and Entisols	Evergreen to semi-evergreen vegetation depending on rainfall. Oxisols (Humic Ferrasols) and Ultisols (Humic Acrisols) Andosols (volcanic soils)
Major geographical spread (of areas with AF importance)	All tropical continents, especially south-east and south Asia, west Africa and Central and South America; about 35% of tropical land	Savanna and sub-Saharan zones of Africa, Cerrado of South America, semi-arid and arid parts of Indian subcontinent approx. 45% of total tropical land	Asia (Himalayan region, some parts of 8” southern India and S.E. Asia), east and central African highlands, Andes; about 20% of tropical land
Main land-use systems	Commercial forestry, agricultural tree crop plantations, rice-paddies (esp. Asia), ranching (S. America), shifting cultivation, arable cropping	Arable farming, extensive ranching or nomadic pastoralism, perennial crop husbandry towards the more humid areas, forestry	Arable farming, plantation agriculture and forestry, ranching in (south and central America), shifting cultivation
Main land-use and ecological problems	Excessive deforestation (and consequent shortening of fallows, etc.) overgrazing, soil acidity and consequent problems, low soil fertility, high rainfall erosivity	Drought (in areas with less rainfall), soil fertility decline caused by over-cultivation, over-grazing, degradation of deciduous woodland, fuelwood/fodder shortage	Soil erosion; shortening of fallows; over-grazing, deforestation and ecosystem degradation; fodder/fuel shortage
Major agroforestry emphasis	Improved fallows, soil fertility improvement and conservation, food production	Fuelwood/fodder production, soil- fertility improvement, windbreaks and shelterbelts, food production	Soil conservation, fodder/ fuel production, watershed management, ecosystem stabilization and protection of rare species

Source: Nair (1989)

countries. Most nations in the tropics are poor according to the international criteria, with gross domestic product lower than the World Bank’s definitions [For the 2019 fiscal year, low-income economies are defined as those with a gross national income (GNI) per capita of $995 or less in 2017; lower-middle-income economies are those with a GNI per capita between $996 and $3,895, and so on: https://blogs.worldbank.org/opendata/new-country-classifications-income-level-2019-2020]. Economic growth seldom keeps pace with population increase. A vast majority of the people work and depend on the land for their livelihood, yet agricultural production per unit area is very low. Although the number of people dependent on agriculture has been declining in countries such as India and China and agricultural productivity has shown remarkable increases in many parts of the world, extreme poverty and very low land-productivity levels are characteristic of several countries/regions of the tropics.

4.3 Distribution of Tropical Agroforestry Systems

The inventory of agroforestry systems (Chapter 3) resulted in several publications on indigenous agroforestry systems in the tropics and subtropics. This information was later compiled into a single volume, *Agroforestry Systems in the Tropics* (Nair 1989). Numerous other publications that describe indigenous agroforestry systems, as well as agroforestry applications for special situations, became available, especially during the early decades of the "agroforestry era" (the 1980s and 1990s), and the trend has continued since. Notable among these include *Systemas Agroforestales* (Montagnini 1986), *Agroforesterie et* Desertification (Baumer 1987), *Agroforestry in* Dryland Africa (Rocheleau et al. 1988), *Agroforestry: Classification and Management* (MacDicken and Vergara 1990), *Agroforestry Systems in* China (Zhaohua et al. 1991), *Agroforestry: Principles and Practices* (Jarvis 1991), *Agroforestry in* India (Tejwani 1994), *Agroforestry in Sustainable Agricultural Systems* (Buck et al. 1999), *Tropical Agroforestry* (Huxley 1999), *The Overstory Book* (Elevitch 2004), *Tropical Agroforestry* (Atangana et al. 2014), and *Agroforestry for the Management of* Waterlogged Saline Soils *and Poor-Quality Waters* (Dagar and Minhas 2016). Some of these authors have multiple books on the topic, but only one is listed here. Indeed, most proceedings of various conferences and meetings on agroforestry held since the beginning of the agroforestry era contain descriptions of agroforestry systems. A Google search on Best Books on Agroforestry lists more than 50 titles, not to mention the voluminous journal articles, reports, and so on. The bottom line is that a vast body of literature on tropical agroforestry systems and practices is available today.

A general overview of the most common agroforestry systems in different parts of the tropics and subtropics is given in Table 4.2. A closer examination of the distribution of these systems in different ecological and geographical regions of the world reveals that there is a clear relationship between the ecological characteristics of a region and the nature of the current agroforestry systems there. The following sections examine this relationship for the three major ecological regions of the tropics.

4.3.1 Lowland Humid and Sub-humid Tropics

Characterized by hot, humid climate (average annual temperature of at least 24 °C for all or most of the year), and an evergreen or semi-evergreen vegetation, the lowland humid and subhumid tropics (hereafter referred to as humid tropics) is by far the most important ecological region in terms of the total human population it supports, extent, and diversity of agroforestry and other land-use systems. Because of the climatic conditions that favor the rapid growth of numerous plants, various types of agroforestry plant associations can be found in areas with the high human population. As a result, various forms of homegardens, shaded-perennial crop combinations, and multilayer tree gardens abound in such regions. In areas with low population density, such as the low *selvas* of Latin America, trees on rangelands and pastures, improved fallow in shifting cultivation areas, and multipurpose tree woodlots are the major agroforestry systems. Thus, the common agroforestry systems in this zone are:

- Shifting cultivation and Taungya
- Homegardens
- Shaded perennials
- Various forms of tree intercropping

The lowland humid tropics also include areas under natural rainforests. Historically, in such areas, the cutting of rainforests has exceeded the rates of natural or managed forest regeneration. A related problem was the shortening of fallow periods in the shifting cultivation cycles and the consequential soil productivity decline and accelerated soil erosion (see Chapter 5). The potential of appropriate agroforestry systems to combat these problems needs to be exploited in future land-use strategies in this zone.

Table 4.2 An overview of the common agroforestry systems in different parts of the tropics

Subsystems and practices	South Pacific	South-East Asia	South Asia	Middle East and Mediterranean	East and Central Africa	West Africa	American Tropics
AGRISILVICULTURAL SYSTEMS							
Improved fallow (in shifting cultivation areas)		Forest villages of Thailand; various fruit trees and plantation crops used as fallow species in Indonesia	Improvements to shifting cultivation; several approaches e.g., in the north-eastern areas of India		Improvements to shifting cultivation e.g., gum gardens of the Sudan	Acioa barterii, Anthonontha macrophyta, *Gliricidia sepium* etc., tried as fallow species	Several forms
Taungya system	Taro with Anthocephalus and Cedrella trees, and other forms	Widely practiced; forest villages of Thailand an improved form	Several forms, several names		The Shamba system	Several forms	Several forms
Tree gardens	Involving fruit trees	Dominated by fruit trees	In all ecological regions	The Dehesa system, 'Parc Arboreé'			e.g., Paraiso woodlots of Paraguay
Hedgerow intercropping (alley cropping)		Extensive use of *Sesbania grandiflora, Leucaena leucocephala* and *Calliandra calothyrsus*	Several experimental approaches e.g., conservation farming in Sri Lanka		The corridor system of Zaire	Experimental systems on alley cropping with Leucaena and other woody perennial species	Experimental
Multipurpose trees and shrubs on farmlands	Mainly fruit or nut trees e.g., *Canarium, Pometia, Pandanus, Barringtonia, Artocarpus altilis*	Dominated by fruit trees: also Acacia mearna cropping system, Indonesia	Several forms in lowlands and highlands, e.g., Khejri-based system in dry parts of India, hill farming in Nepal	The oasis system; crop combinations with carob trees; the Dehesa system; olive trees and cereals; irrigated systems	Various forms; the Chagga system of Tanzanian highlands; the Nyabisindu system of Rwanda	Faidherbia (Acacia) albida-based systems in dry areas; Butyrospermum and Parkia systems 'Parc arboreé'	Various forms in all ecological regions
Plantation crop combinations	Plantation crops and multipurpose trees e.g., *Casuarina* with coffee in the Papua New Guinea highlands; also *Gliricidia* and	Plantation crops and fruit trees; smallholder systems of crop combinations with plantation crops;	Integrated production systems in smallholdings; shade trees in plantations; other crop mixtures	Irrigated systems; olive trees and cereals	Intergrated production; shade trees in commercial plantations; mixed systems in the highlands	Plantation crop mixtures; smallholder production systems	Plantation crop mixtures; shade trees in commercial plantations; mixed systems in small-holdings; spice

(continued)

Table 4.2 (continued)

Subsystems and practices	South Pacific	South-East Asia	South Asia	Middle East and Mediterranean	East and Central Africa	West Africa	American Tropics
	Leucaena with cacao	plantation crops with spice trees	including various spice trees				trees; babassu palm-based systems
Agroforestry fuelwood production	Multipurpose fuelwood trees around settlements	Several examples in different ecological regions	Various forms, including social forestry systems		Various forms	Common in the dry regions	Several forms in the dry regions
Shelterbelts, windbreaks, soil conservation hedges	*Casuarina oligodon* in the highlands as shelterbelts and to improve soils	Terrace stabilization on steep slopes	Use of *Casuarina* spp. as shelterbelts; several windbreaks	Tree species for erosion control	The Nyabisindu system of Rwanda	Various forms	Live-fences, windbreaks, especially in highlands
SILVOPASTORAL SYSTEMS							
Protein bank (cut-and-carry) fodder production	Rare	Very common, especially in highlands	Multipurpose fodder trees on or around farmlands, especially in highlands		Very common	Very common	Very common
Live-fences of fodder trees and hedges	Occasional	Leucaena, Calliandra e.g., used extensively	Sesbania, Euphorbia, Syzigium, etc., are common		Very common in all ecological regions	Very common in highlands	
Trees and shrubs on pasture	Cattle under coconut, pine and *Eucalyptus deglupta*	Grazing under coconut and other plantation crops	Several tree species being used very widely	Very common in dry regions; the Dehesa system	The *Acacia*-dominated system in the arid parts of Kenya, Somalia and Ethiopia	Cattle under oilpalm; cattle and sheep under coconut	Common in humid as well as dry regions e.g., grazing under plantation crops in Brazil
AGROSILVOPASTORAL SYSTEMS							
Woody hedges for browse, mulch, green manure, soil conservation etc.	Various forms; Casuarina oligodon widely used to provide mulch and compost	Various forms	Various forms, especially in lowlands		Common; variants of the Shamba system	Very common	Especially in hilly regions

Homegardens (involving a large number of herbaceous and woody plants and/or livestock)	Several types of homegardens and kitchen gardens	Very common; Java homegardens often quoted as good examples; involving several fruit trees	Common in all ecological regions; usually involving fruit trees	The oasis system	Various forms; the Chagga homegardens; the Nyabisindu system	Compounds farms in humid lowlands	Very common in thickly populated areas
OTHER SYSTEMS							
Agrosilvo fishery (aquaforestry)		Silviculture in mangrove areas; trees on bunds of fish-breeding ponds	Occasional				
Various forms of shifting cultivation	Common	Swidden farming and other forms	Very common; various names		Very common	Very common in the lowlands	Very common in all ecological regions
Apiculture with trees	Common	Common	Common	Common	Common	Common	

Source: Nair (1989)

4.3.2 Semiarid and Arid Tropics

Extending over the savanna and Sudano-Sahelian zone of Africa, the Cerrado of South America, and large areas of the Indian subcontinent, and several other regions, the semiarid and arid tropics cover about 35% of the tropical and subtropical landscape that is characterized by one or two wet seasons (Köppen Aw or Aw', respectively) and at least one long dry season. Drought, which is a major hazard, and population pressure are the main factors that determine the type of agroforestry systems in this zone. Although homegardens and multilayer tree gardens are found in the wetter areas with high population pressure, the predominant agroforestry systems in this zone are:

- Various forms of silvopastoral systems
- Extensive tree intercropping (e.g., the Parklands of West Africa)
- Windbreaks and shelterbelts
- Multipurpose trees on croplands

Experience with tropical alley cropping that was a major agroforestry research theme during the 1980s and 1990s was not promising in the semiarid tropics (see Chapter 6). This has led to some serious but misconstrued criticisms being leveled against agroforestry in general for these regions. The criticisms were based on the classic "one-size-fits-all" misconception of equating alleycropping with agroforestry without recognizing that no single land-use practice (be it in the broad realm of agroforestry or agriculture) fits all ecological regions. Indeed, some of the best-known agroforestry systems are found in the semiarid tropics – for example, extensive intercropping of millets under *Faidherbia (Acacia) albida* trees in Africa (the Parklands system of West Africa: Boffa 1999), and under the "khejri" (*Prosopis cineraria*) trees in the dry areas of India (Shankarnarayan et al. 1987). Agroforestry systems are also commonly used for addressing other major land-use problems of the region such as fuelwood shortage and desertification.

4.3.3 Tropical Highlands

Approximately 20% of the tropical lands are at elevations from 900 – 1800 m. These areas include about half of the Andean highlands of Central and South America, parts of Venezuela and Brazil, the mountain regions of the Caribbean, many parts of East and Central Africa, Cameroon, the Deccan Plateau of India, and some parts of the southeast Asian mainland. The altitude exceeds 1800 m in about 3% of the tropical area in the Andes, the Ethiopian and Kenyan Highlands, northern Myanmar, and parts of Papua New Guinea. In the subtropical regions, the most important highlands are in the Himalayan region.

The highland tropics with significant agroforestry potential are humid or subhumid, while areas with dry climates are of very low agricultural potential. Land-use problems in the highlands are comparable to those in humid or dry lowlands depending on the climate, with the addition that sloping lands and steep terrains make soil erosion an issue of major concern. Moreover, the overall annual temperatures are low in the highlands (for every 100 m increase in elevation in the tropics, there is a decline of 0.6 °C in the mean annual temperature); this affects the growth of certain lowland tropical species.

The main agroforestry systems in tropical highlands are:

- Production systems involving shaded perennial (plantation) crops such as coffee and tea in commercial as well as smallholder systems,
- Use of woody perennials in soil conservation and soil fertility maintenance,
- Improved fallows, and
- Silvopastoral systems.

The major types of agroforestry system subgroups are summarized in Table 4.3.

Table 4.3 Global distribution and area under different agroforestry system sub-groups†

AFS sub-group	Major AF Practices	Distribution (major agro-ecol./geographical regions) ‡		Approx. area (million ha) ‡	
		Tropical	Temperate	Tropical	Temperate
Multistrata systems	Homegardens	Humid: wet, moist, and montane (rainfall >1000 mm yr^{-1})		100	
	Shaded perennials		Forest farming		
Tree intercropping	Alley cropping	Rainfall > 800 mm yr^{-1}	N. America, Europe	50	50
	Trees on farmlands	Throughout tropics	N. America, Europe	550	50
Silvopasture	Cut-and –carry and browsing	Wet and moist; rainfall >1000 mm yr^{-1}		300	150
	Grazing under trees	Semiarid to arid	N. America, Europe, subtropical highlands		
Protective systems	Windbreaks, shelterbelts	Semiarid and arid lands; coastal areas	N. America, Europe, China	200	100
	Soil conservation hedges	Sloping lands in higher rainfall areas	N. America (Riparian buffer strips)		
	Boundary planting	Throughout	Windbreaks		
Agroforestry woodlots	Firewood and fodder	Drylands		50	
	Land reclamation	Degraded lands (eroded, salt-affected)			
TOTAL				1,250	350

†Estimates based on the reported values in literature
‡Including potential areas for adoption
Source: Nair (2012, 2014)

4.4 Agroecological Spread of Tropical Agroforestry Systems

The type of agroforestry system found in any location is determined to a major extent by agro-ecological factors. Socioeconomic factors such as human population pressure, availability of labor, and proximity to markets are also important determinants, such that considerable variations can be found among systems existing in similar or identical agroclimatic conditions. Sometimes socioeconomic factors take precedence over ecological factors in determining the appropriate type of agroforestry practices for a region. Even in the case of systems that are found in many ecological and geographical regions, numerous variants are specific to certain socioeconomic contexts. In general, it can be said that while ecological factors determine the major type of agroforestry system in a locality, the complexity of the system and the intensity with which it is managed increase in direct proportion to the population intensity and land productivity of the area.

The multispecies, multistoried homegarden systems serve to illustrate some of these points. Although these systems are found mainly in humid lowlands, they are also common in pockets of high population density in other ecological regions (see Chapter 7). Fernandes and Nair (1986) found in an analysis of the structural and functional aspects of 10 homegarden systems in different ecological regions that although the average size of a homegarden unit is less than 0.5 ha, it generally consists of numerous woody and herbaceous species. The garden is carefully structured so that the canopies of the different species are oriented in three to five layers at varying heights, with each component having a specific place within the overall design.

Agroecological factors have a considerable bearing on the functional dynamics of agroforestry practices. For example, the primary function of agroforestry practices in sloping lands is erosion control and soil conservation; in wind-prone areas, the emphasis is on windbreaks and shelterbelts; and, in areas with a fuelwood shortage, the emphasis is on fuelwood production. There are also specific agroforestry approaches to the reclamation of degraded lands or wastelands (for example, land that has been badly eroded or overgrazed, or is highly saline or alkaline). The preponderance of homegardens and other multispecies systems in fertile lowlands and areas with high agricultural potential at one end of the ecological scale, and extensive silvopastoral practices at the other, with various systems in between, indicates that the ecological potential of an area is the prime factor that determines the distribution and extent of adoption of specific agroforestry systems.

The ecological and geographical distribution of the major agroforestry systems in the world has been schematically presented by Nair (1989). Caution must be exercised, however, in producing and interpreting such "agroforestry maps" because they aim to show general distribution patterns and thus include only those areas in which specified agroforestry systems are abundant. Innumerable location-specific agroforestry systems exist in the tropics which, although important in certain respects, are not significant enough in terms of the overall economy and land-use pattern of the area in which they operate to warrant inclusion on a global map. Conversely some practices, such as multipurpose trees on farmlands are found in almost all ecological and geographical regions, but only a few are classified as distinct agroforestry systems and included on an agroforestry map.

A significant feature that emerges from this analysis is that irrespective of the sociocultural differences in different geographical regions, the major types of agroforestry systems are structurally similar in areas with similar ecological conditions. Thus, agroecological zones can be taken as a basis for the design of agroforestry systems, the underlying concept being that areas with similar ecological conditions can have structurally similar agroforestry systems. This strategy is used by development agencies for designing various agroforestry research networks on a national/regional basis (see, for example, Nair 1992). Such matrices of agroecological conditions versus agroforestry practices could be developed for any region, although the agroecological conditions and the biological and socioeconomic characteristics of agroforestry systems are so complex and varied that it would be difficult to integrate all this information into simple models. Knowledge-engineering applications such as Decision Support Systems have been attempted (e.g., Warkentin et al. 1990; Ellis et al. 2004; Moser and Bentrup 2017), but do not seem to have made any significant progress in tropical applications.

4.5 The Temperate Environment and Land Use Systems

Areas with temperate climate have large temperature extremes during the year; they have cold winters and warm rainy seasons. While the northern portions of the temperate region feature Boreal, Continental, and Oceanic climates, the lower latitudes have Mediterranean and subtropical climates. A basic definition encompassing all these different climates is that the temperate zone has a mean temperature in the range of −3 °C to 18 °C in the coldest month. The winter temperatures will be milder in lower latitudes in both northern and southern hemispheres (nearer the equator) and colder in the higher latitudes.

From the agroforestry – and agricultural – standpoint, the distinction between tropical and temperate zones, especially in the borderline areas in both hemispheres is based not strictly on climatic or geographical factors, but a combination of factors including socioeconomic conditions and developmental status of the regions. As mentioned in Section 4.2, tropical regions are generally in the lower strata of economic development and industrialization, and most countries of the tropics are the so-called developing nations, as opposed to industrialized

North America, Europe, and the other so-called developed nations. Temperatures and vegetation in most subtropical zones can be somewhat comparable to those of the tropics for much of the year, and the practice of agroforestry in the subtropical parts of developing countries (e.g., of the Indian subcontinent) are comparable to that of the tropical than the temperate regions. For these reasons, temperate agroforestry refers to agroforestry practiced in the temperate regions of the world generally between latitudes 30° and 60°. The USA and Canada, Europe, southern Australia, and New Zealand constitute the main temperate countries/regions from the agroforestry perspective.

4.6 Temperate Agroforestry Practices

Developments in agroforestry applications have taken place in a rather simultaneous and parallel manner in both the major temperate-zone continents of North America (the USA and Canada) and Europe since around the 1990s. Europe, with its long history of land use practices and traditions, had some agroforestry-like practices right from the Roman times until the onset of industrial agriculture during the post-World War II (Eichhorn et al. 2006). In the USA and Canada, however, there was no such historic precedent, and agroforestry is considered a new science and set of practices tailored to address numerous sustainability issues associated with production agriculture (Gold and Garrett 2009).

According to the agroforestry system classification based on nature and arrangement of components explained in Chapter 3, the two most common types of temperate-zone systems have been the agrisilvicultural use of windbreaks and riparian buffers for soil protection and environmental amelioration, and silvopastoral practices with livestock in different woodland and range ecosystems. Agrisilvicultural combinations of nut- or fruit trees and herbaceous crops are also common. Agroforestry systems in the temperate zones, however, are not classified according to component-based classification scheme; instead, the practices are grouped under a few distinct categories as mentioned in Chapter 3 (Tables 3.3 and 3.4). Although there are remarkable similarities between the North American and European agroforestry practices of the same names (such as alleycropping, silvopasture, windbreaks, etc.), some minor differences exist, which arise primarily from the location specificity of the practices. There is also one practice in the list of European agroforestry practices called kitchen garden or homegarden, an equivalent for which does not exist in the US and Canada literature.

4.7 Temperate vs. Tropical Agroforestry

The seasonality of climate in the temperate regions that includes distinct warm and cold seasons engenders some unique agroforestry qualities. In the tropics, the same crops may be produced throughout the year, whereas individual crops in the temperate zone are generally restricted to one or rarely two seasons a year and fewer crops are grown each year. Therefore, unlike the great variety of systems and practices in the tropics, only a few agroforestry systems are practiced in the temperate region. Socioeconomic conditions in the developed countries of the temperate zone have strongly influenced land-use practices such that the production objectives and outlook of temperate agroforestry practitioners are quite different from those of the tropics. Although small farms were historically dominant in the temperate zone, and still are in many regions, there has been a significant trend in the 20th century towards large, family, corporate, or communal farms where production is largely concentrated on a few crops for local and distant markets. Agroforestry applications on such farms have often focused on one or two high-value crops and include high levels of mechanization. Combinations of trees and agriculture are opportunistically perceived as a strategy for improving economic profitability. This is in sharp contrast to the tropical practices that are most frequently found on small individual farms or sharecropped and community lands where production is often for subsistence consumption or local markets and a large variety of crops are both available and necessary in most family settings. The major motivation for adopting agroforestry in the temperate zone is the increasing realization of the environmental benefits offered by the presence of trees on agricultural lands such as protection of soil- and water quality, climate change mitigation, and biodiversity conservation. In the tropical settings where food security is the primary concern, such environmental benefits, although appreciated, are seldom the top priority for the smallholder farmers. These contrasts between the tropical and temperate agroforestry systems in terms of their focus on addressing the "top ten" land-use challenges are presented in Figure 4.1.

Another significant attribute of temperate-zone agroforestry is that a substantial knowledge base is available and market values have been established for the components used (trees, crops, animals) especially for trees. Research in the region over more than a century has provided information on genetic variability, physiological characteristics, and cultural requirements for a wide variety of species, many of which have also been important in wood products markets. Thus, the detailed information base and dependable markets are strong incentives for incorporating many temperate species in agroforestry systems, as opposed to the underexploited and unknown nature of species and lack of market and other support services that are so characteristic of tropical agroforestry systems.

4.8 Geographical Distribution and Area Under Agroforestry Systems

Estimating the area under agroforestry on a farm is a challenge because of the lack of clarity and proper procedures for delineating the area influenced by trees in a mixed stand of trees and crops (Nair et al. 2009). In simultaneous systems, the entire area occupied by multistrata systems such as homegardens and shaded perennial systems and intensive tree-intercropping situations can be listed as agroforestry. However, many agroforestry systems are rather extensive where the components, especially trees, are not planted at regular spacing or density; for example, the parkland system and extensive silvopasture. Such situations exist also in Europe and other temperate regions where mosaics of intensive field systems, with hedgerows and patches of woodland, are common features of agricultural landscapes. The problem of estimating the area under agroforestry is more difficult in the case of practices such as windbreaks and boundary planting where the trees are planted at wide distances between rows (windbreaks) or around agricultural or pastoral parcels (boundary planting), and the influence of trees both above and below ground

Figure 4.1 Agroforestry and the top ten land-use challenges

extends beyond the visible area of influence of the trees. For windbreaks, the rule of thumb is that the area protected from wind erosion extends laterally to 10 times the height (H) of trees in the central core of windbreaks (see Chapter 18). The problem has a different dimension when it comes to sequential tropical systems such as improved fallows and shifting cultivation. In such situations, the beneficial effect of trees and other woody vegetation (in the fallow phase) on the crops that follow them (in the cropping phase) is believed to last for a variable length of time (years). Despite these temporal and spatial issues, an ICRAF survey using high-resolution remote-sensing quantified the areas of agricultural landscapes with at least 10% tree cover worldwide as nearly a billion hectares in the tropics (Zomer et al. 2009). Zomer et al. (2016) estimated that the area of agricultural land with at least 10% tree cover – currently 43% of all agricultural land – had increased by 2% during the previous 10 years globally. The area under agroforestry in Europe is currently estimated at about 20 million ha (Mosquero-Losada et al. 2012; AGFORWARD 2017). The potential area available for agroforestry in the United States is estimated as 143.7 million ha (Jose et al. 2012); although such area estimates are not available for Canada, windbreaks and shelterbelts are reported as the most widespread agroforestry practice extending over 200,000 km in the Prairie Region and 10,000 km in Quebec Region (Thevathasan et al. 2012). Based on these estimates and considering the prevalence of agroforestry practices in non-agricultural lands, Nair (2012, 2014) estimated the global area under agroforestry as 1.6 billion ha. This is, however, an estimate; no matter how experience-based, it is still a guesstimate!

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Section II

Agroforestry Systems and Practices

5 Shifting Cultivation and *Taungya*

Contents

Abstract

Shifting Cultivation or swidden farming is considered the oldest form of agriculture. It refers to the traditional, centuries-old farming system, in which land under natural vegetation is cleared, cropped – usually with food crops – for a few years, and then left untended allowing the natural vegetation to regenerate; a few years later, the farmer returns to that land, clears it again, and resumes crop cultivation; and the "crop – fallow – crop – fallow –" cycle is repeated indefinitely. Despite decades of efforts to eradicate, improve, or replace it, the practice in some form is still followed in about 300 million ha in the tropics. Although denigrated as resource-depleting and environmentally destructive, these traditional practices offer insights into the role of the woody vegetation in recouping the soil fertility that is depleted during the cropping phase. Taungya is a special form of land management based on the well-known German system of *Waldfeldbau* (cultivation of agricultural crops in forests) and was developed in Burma (today's Myanmar) in the mid-1800s as an improvement to the traditional slash-and-burn type of shifting cultivation, primarily for promoting forest plantation establishment with

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the help of the land-hungry farmers. The practice became so popular that most of the forest plantations in the tropical world, particularly in Asia and Africa, were established in the taungya way. Decades of research to find improvements and/or alternatives to shifting cultivation has established the importance of retaining or incorporating woody vegetation for sustaining soil productivity as a key scientific foundation of modern agroforestry. Tropical alley cropping and improved fallows were the two major tropical agroforestry-research efforts in the late 1990s based on the concept of fallow improvement.

5.1 Introduction

In the next seven chapters including this one, we will review and summarize the major types of agroforestry practices, past and present. These include the experiences with the traditional practices that had been followed for long, which gradually evolved or were intentionally transformed with technical improvements, into today's practices. Following this chapter that presents the experiences with shifting cultivation, Chapter 6 will focus on tropical alley cropping and the so-called "improved fallows" that represent the major efforts in capitalizing on the soil-improving potential of trees and shrubs. The advances in understanding the enigma of the multispecies, multistrata tropical homegardens and shaded perennial systems will be covered in Chapters 7 and 8 respectively. Chapter 9 will be devoted to silvopastoral systems that exemplify the role of trees in supporting animal production. Given that the emphasis in all these chapters is on tropical situations, a special chapter (Chapter 10) will summarize the efforts in agroforestry in the temperate regions. Chapter 11 will then conclude this major section of the book by discussing the "other" agroforestry systems and practices that are not covered in the preceding chapters. Thus, these seven chapters will summarize the experience with the major agroforestry systems and practices and will set the stage for discussing the foundations of scientific developments in agroforestry during the four decades since 1980.

5.2 Shifting Cultivation

5.2.1 System Overview

Shifting Cultivation or swidden farming is perhaps the oldest form of agriculture, in which trees and crops are grown together on the same unit of land. The term refers to a type of farming system in which land under natural vegetation is cleared, cropped – usually with food crops – for a few years, and then left untended while the natural vegetation regenerates; a few years later, when the farmer is convinced that the fertility of the land that was left behind had been restored, he/she returns to that land, clears it again, and resumes crop cultivation there. Shifting cultivation is said to have been widespread in Europe until a few centuries ago (Nye and Greenland 1960; Greenland 1976). Under resource-sufficient conditions, as in Europe, shifting cultivation was slowly replaced by more technologically oriented and profitable land-use systems with little or no resemblance to the original system. On the other hand, shifting cultivation and its variants are still a major form of a traditional farming system over vast areas of the tropics and subtropics (Figure 5.1).

The practice is known by different local names in various places (Table 5.1), depending on the local environmental and sociocultural conditions and historical features. Numerous publications on such practices were produced during the last few decades of the 20th century (the 1960s to the 1990s), including Conklin (1963); Spencer (1966); FAO/SIDA (1974); Grandstaff (1980); Ruthenberg (1980); Kyuma and Pairinta (1983); Denevan et al. (1984); FAO (1984); Padoch et al. (1985); Padoch and de Jong (1987); and Ramakrishnan (1992). Among the more recent publications, the most voluminous are Malcolm Cairn's trilogy of volumes (Cairns 2007, 2015, 2017), each involving contributions of an average of 100 scholars in more than 50 chapters and 1,000 pages of descriptions and analyses of numerous examples of the practice in South-

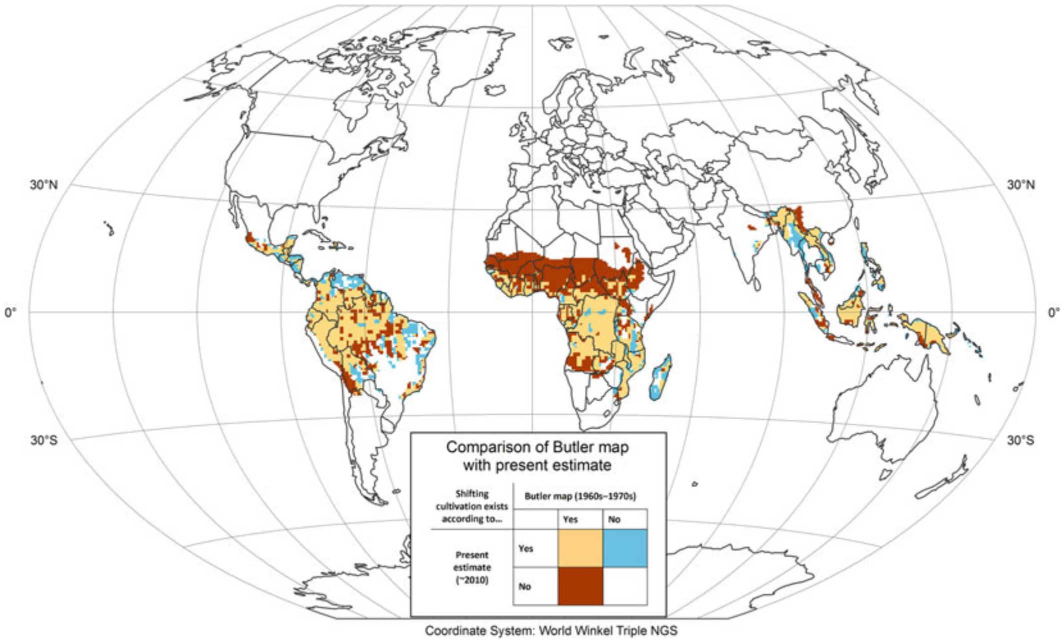

Figure 5.1 Global status of shifting cultivation around 2010 [in comparison with the Butler map (Butler 1980) showing the status in the 1960s to 1970s]. The figure was elaborated using ArcGIS 10.4. (Source: Heinimann et al. 2017)

Table 5.1 Local terms for shifting cultivation in different places

Region	Country	Local terms[a]
Africa	Congo (Zaire)	*C(h)itemene*
	Ghana	*Proka*
	Kenya, East Africa	*Shamba*
	Madagascar	*Tavy*
	Southern Africa	*Chitemene, Citimene*
Asia	India	*Jhum, Kumri, Pothu*
	Indonesia, Malaysia	*Ladang*
	Laos	*Hay/Ray*
	Myanmar (Burma)	*Taungya*
	Philippines	*Hanumo, Kaingin*
	Sri Lanka	*Chena*
	Thailand	*Tam-ray, Rai*
	Vietnam	*Jumar, Luva*
Latin America	Brazil	*Roca*
	Central America	*Milpa, Conuco*
	Mexico	*Milpa, Coamile*

[a]Note: Swidden is an old English term used for shifting cultivation in many contexts
Source: Modified from Nair (1993)

and Southeast Asia. Although the practice has been prevalent in other parts of the developing world in Africa and Latin America too though not as extensively as in Asia, nothing comparable and voluminous as Cairns' publications have been produced from those regions. The efforts of the numerous scholars who contributed to these volumes as well as studies from other parts of the world over the years have brought to light documented evidence of the innumerable examples of a variety of fallow- and tree-cropping systems and their management by the indigenous people.

Most of these reports are heavily focused on social and anthropological attributes and descriptions of how they have been managed over long periods, with relatively little on the biophysical underpinnings that are essential for suggesting science-based alternatives and improvements. Because of the remoteness of the areas where such systems are practiced and the lack of any discernible social and political power for the practitioners who are predominantly poor and hapless, such systems have not attracted any significant research investment and attention. Consequently, there has been an enduring perspective right from the colonial times within the academic and development circles to look down upon and denigrate shifting cultivation as an unproductive, disorderly, resource-depleting, and environmentally destructive practice of the past leading to calls for its abandonment and prohibition as alluded to by Colfer (2017). In many areas in the tropics, the local and national governments faced with such mounting criticisms and negative characterization of shifting cultivation have been under severe pressure from various domestic and international entities to replace shifting cultivation with better land-use options. For a student of agroforestry, however, these traditional systems offer valuable insights into how trees have been an integral part of low-input agricultural systems, what roles trees and other woody perennials play during the fallow phase of the shifting cultivation cycle in recouping the soil fertility that is depleted during the cropping phase, and to what extent these systems adapt to changing land-use patterns and market economics. With this background, this chapter will stay focused on a short overview of the past, present, and future of this age-old practice with an emphasis on the lessons learned and experience gained from efforts in improving it without entering into describing the innumerable variants of the practice that have already been documented in literature as stated above.

The Extent of Area Under Shifting Cultivation: Rigorous estimates of the area under shifting cultivation and the number of people dependent on it are not available. This is primarily because the practice encompasses a variety of land-management traditions practiced by poor, often migratory farmers who neither have legal rights to the land they cultivate nor practice sedentary farming according to any "package of practices" that are commonly followed in settled farming systems. According to FAO estimates that have traditionally become "authentic" by repeated citations, the practice covered approximately 360 million hectares or 30 percent of the exploitable soils of the world and supported over 250 million people during the early 1980s. Crutzen and Andreae (1990) projected the number of people practicing shifting cultivation as 200 million, and the area as 300 million to 500 million hectares in the tropics, whereas Mertz (2009) estimated that 300 million to 500 million shifting cultivators live in 40 to 50 countries, mainly in mountainous and upland regions. Although the system is dominant mainly in sparsely populated and lesser developed areas, it is found in most parts of the tropics especially in the humid and subhumid tropics (Mertz et al. 2009). From a meta-analysis of qualitative assessments of land-cover transformations in tropical forest-agriculture frontiers based on a total of 111 publications with information on 157 sites (92 in Asia and Pacific, 20 in Africa, and 45 in Latin and Central America), van Vliet et al. (2012) reported that swidden agriculture decreased in landscapes with access to markets. The authors' prognosis was that despite the global trend toward land-use intensification, in many areas swidden will remain part of rural landscapes as the safety component of diversified systems. Heinimann et al. (2017) reported a study that combined the existing global Landsat-based deforestation data covering the years 2000 to 2014 with very high-resolution satellite imagery to visually detect the specific spatio-temporal pattern of shifting cultivation worldwide. The study, with a reported overall accuracy above 87%, showed signs of shifting cultivation being widespread estimated that shifting cultivation landscapes currently covered roughly 280 million hectares worldwide (Figure 5.1). Based on their results and historical trends, the authors suggested a possible strong decrease in shifting cultivation over the next decades, which also raised issues of livelihood security and resilience among people currently depending on the practice.

5.2.2 The Common Activities in the Practice of Shifting Cultivation

Land clearing for shifting cultivation is usually done manually using simple hand tools by the slash-and-burn method, and therefore the practice is sometimes known – unfortunately in a denigrative and pejorative manner – as "slash-and-burn" agriculture. The cultivation phase is usually short (2–3 years), but the regeneration phase, known as the fallow or bush-fallow phase, is much longer (traditionally 10–20 years). In many temperate regions such as North America and Europe, the term "fallow" means bare land or land taken out of cultivation often as a result of government subsidy programs, or when a year of cropping is skipped to recharge subsoil water in semiarid areas (Weil and Brady 2017). In tropical settings, the term has a different meaning: it refers to the period when land is not cropped to facilitate biomass accumulations. During the land-clearing phase, useful trees and shrubs are left standing and are sometimes lightly pruned; other trees and shrubs are pruned down to stumps of varying height to facilitate fast regeneration and support for climbing species that require staking; and the remaining vegetation and debris are burned, after which crops (seeds) are sown with the onset of rains. The lengths of the cropping and fallow phases vary considerably, the former being more variable; usually, the fallow phase is several times longer than the cropping phase. The length of the fallow phase, when the soil that had been depleted of its fertility during the cropping period regains some of its fertility through the natural regenerative impact of the woody vegetation, is considered critical to the success and sustainability of the practice (Figure 5.2: Ruthenberg 1980). Some photographs of shifting cultivation practices in different parts of the tropics are presented in Figures 5.3 to 5.11; also see Figure 1.10 (Chapter 1).

The shifting cultivation practice that is common in sub-Saharan Africa is the bush-fallow system, which entails the slash-and-burn method described above with alternating cycles of cropping and bush-fallow phases. In the semiarid and sub-humid zones of West Africa, farmers have maintained for generations another traditional land-use known as the ***Agroforestry Parklands*** system, which is characterized by the deliberate retention of trees on cultivated or recently fallowed land (Boffa 1999). Trees are an integral part of the system, providing food, fuel, fodder, medicinal products, building materials, and saleable commodities, as well as contributing to the maintenance of soil fertility, water conservation, and environmental protection. Although traditional management of these parklands entails some elements of shifting cultivation, the Parkland System is considered more as a distinct type of AFS than a subset of shifting cultivation. A short description of the Parkland system is included in Section 9.4.1.

Despite the remarkable similarity of the shifting cultivation practices in different parts of the world, some differences exist among them depending largely on the environmental and sociocultural conditions of the locality and the historical features that have influenced the evolution of land-use systems over the centuries. These variations are reflected, to some extent, in the various names by which the system is known in different parts of the world (Spencer 1966; Okigbo 1985: Table 5.1). In developing countries with low population densities, where the farmer had enough land at his disposal and freedom to cultivate wherever he chose within a specified geopolitical unit or region, the ratio of the length of the fallow period to cultivation phase reached 10 to 1. The system was stable and ecologically sound. Under the strain of increasing population pressure, however, the fallow periods became

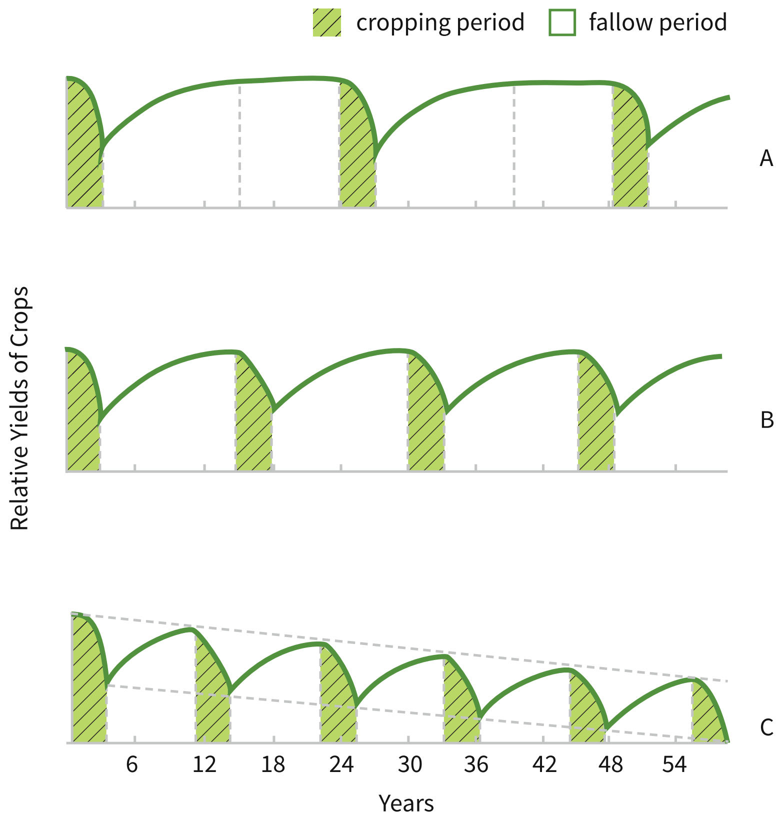

Figure 5.2 Schematic presentation of the changes with time in the length of fallow phase and consequent patterns of crop yields and soil productivity under shifting cultivation. (Source: Ruthenberg (1980), reproduced from the first edition of the book (Nair 1993))

drastically reduced and the system degenerated, resulting in serious soil erosion and a decline in the soil's fertility and productivity (Figure 5.2).

The most remarkable differences in the practice of shifting cultivation are, perhaps, due to ecological conditions. In forest areas of the lowland humid tropics, the practice consists of clearing a patch of the forest during the dry (or lowest rainfall) period, burning the debris *in situ* shortly before the first heavy rains, and planting crops, such as maize (*Zea mays*), rice (*Oryza sativa*), beans (mostly *Phaseolus* spp. and *Vigna* spp.), cassava (*Manihot esculenta*), yams (mostly *Dioscorea* spp.), and plantain (*Musa* sp.), amidst the burned and decaying debris. The crops are occasionally weeded manually. Thus, irregular patterns of intercropping are the usual practices (Figures 5.5 to 5.8). After two or three years of cropping, the field is abandoned to allow rapid regrowth of the forest. The farmer returns to the same plot after 5 to 20 years, clears the land once again, and the cycle is repeated. In an example of shifting cultivation as practiced in the savannas, especially in West Africa, the vegetation, consisting primarily of grasses and some scattered trees and bushes, is cleared and burned in the dry season (Figures 5.8 and 5.9). The soil is then worked into mounds, about 50 cm high, on which root crops, usually yams, are planted. Maize, beans, and other crops are planted between the rows. The mounds are leveled after the first year of yams. A variety of crops including maize, millets, and peanuts (groundnuts: *Arachis hypogaea*) are planted for the following 2 to 3 years. Thereafter, the land is left fallow and regrowth of coarse grasses and bushes occurs. This period lasts for up to about ten years. Compared with shifting cultivation in the forests, this form results in a more thorough working of the soil for cropping, longer cropping periods, and, ultimately, a more severe weed infestation. Moreover, soil erosion hazards are also higher when

Figure 5.3 *Jhooming* in the Northeastern hilly region of India. (Photo: PKR Nair 1984)

the soil is bare after the clearing and burning in the dry season.

5.2.3 Soil Management Under Shifting Cultivation

Evolutionary trends in tropical cropping systems show that management intensities capable of sustaining productivity are usually introduced only after considerable depletion and degradation of non-renewable resources such as soil have taken place. Productivity levels that can be sustained in cropping systems largely reflect the potential and degree of management of the resource base. High productivity comes only from systems where management intensities necessary for sustainability are attained without extensive depletion of the resources. Therefore, it is important to understand the role of the fallow period for soil-productivity regeneration in traditional shifting cultivation. Early studies on soils under shifting

Figure 5.4 Slash-and-burn (swidden farming) in Xikrin, Pará State, Brazil. The settlers usually arrive via rivers on rudimentary boats made of local materials, clear a patch of forest, and establish a base from where they advance deeper and deeper into the forest for farming. (Photo: Robert Miller)

Figure 5.5 Shifting cultivation in the Brazilian Amazon region (crop: rice, *Oryza sativa*). Improved practices such as line planting of crops and fertilizer application were recommended for crops grown on deforested land, but seldom adopted by the shifting cultivators. (Photo: PKR Nair 1979)

cultivation have been evaluated by Nye and Greenland (1960), Newton (1960), FAO/SIDA (1974), and Sanchez (2019), and an annotated bibliography of shifting cultivation and its alternatives produced by Robinson and McKean (1992). Many of the approaches suggested as improvements and/or alternatives to shifting cultivation by FAO (1985) emphasized the importance of retaining or incorporating the woody vegetation into the fallow phase – and even in the cultivation phase – as the key to the maintenance of soil productivity, and recognized the length of the fallow phase as a critical factor in terms of sustainability of the system (see Figure 5.2). Depending on how the woody species are incorporated, the alternate land-use system can be Alley Cropping (Kang and Wilson 1987), Improved Fallow systems (Buresh and Cooper

Figure 5.6 Growing crops not only for consumption but also for sale (cash) is increasingly being practiced by shifting cultivators. Photo shows growing cabbage as a cash crop in the swiddens (swidden farming is another term for shifting cultivation) in the uplands of Thailand. Photo, with permission: Malcolm Cairns

Figure 5.7 Shifting cultivators conscientiously follow low-input land-management practices to protect their crops. Infestation by obnoxious weeds such as *Imperata cylindrica* has ravaged vast areas of agricultural fields in the humid lowlands of Southeast Asia, West Africa, and other tropical regions. Shading the weed out by the canopy of overstory species is one of the effective, low-input ways to suppress the weed. Photo shows shifting cultivators using *Tithonia diversifolia*, a fast-growing, high-biomass-producing plant, to suppress *Imperata cylindrica* in the swidden fields in the Philippines. (Photo, with permission: Malcolm Cairns)

1999), some other form of AFS (Nair and Fernandes 1985), or other forms of improved, permanent production systems (Okigbo 1985). To discuss these various options, the major soil management problems in the shifting cultivation areas of the tropics and subtropics need to be reviewed, as well as the role of trees in soil productivity and protection; the former is presented here, the latter is considered in detail in Part IV of this book (especially Chapters 16 and 18).

In the various attempts that have been made to classify shifting cultivation by FAO/SIDA (1974) and reviewed by Ruthenberg (1980), the different

Figure 5.8 The bush fallow system in Africa. The bush fallow system is the wide-spread form of shifting cultivation throughout Africa (see Section 5.2.2)

Figure 5.9 A major part of land preparation for sowing crops at the onset of rains in the extensive semiarid lands of West Africa involves burning out the dry-season vegetation, leaving the trees unharmed, as shown in the photo. (Photo: ICRAF/World Agroforestry)

categories designate different degrees of intensification of cultivation which can best be evaluated based on the land-use factor (L):

$$L = \frac{C + F}{F}$$

where

C= length of the cropping phase (years)
F= length of the fallow phase (years)

*Note: A related term used in some literature (*e.g., Table 5.2*) is the cultivation factor (R), which is the inverse of L, whereby C = R/(C+F) with C and F having the same meanings as in land-use factor.*

Although the length of the fallow phase has been recognized as the most critical factor in terms of the sustainability of the system, there is a misleading tendency, as pointed out by Falvey (2017), to present shifting cultivation as consisting

Table 5.2 Rest period requirements of major tropical soils under traditional annual cropping

Soil type	General description	% area in the tropics	R Factor for major ecozones		
			Rainforest	Savanna	Semiarid
Oxisols	Laterite, highly weathered and leached	23	15	15	20
Ultisols	Leached; more clay than Oxisols	20	15	15	20
Alfisols	Red soils; medium fertility	15	25	30	35
Vertisols	Cracking clay	~ 5	40	55	45
Entisols	Alluvial, sandy	16	10	15	20
Inceptisols	Brown, forest soils	14	40	55	75

R, the cultivation factor = [C/(C+F)] × 100
C = number of years under cultivation; F = number of years under fallow
Growing periods (# days per year): Rainforest > 270; Savanna > 120 – 270; Semiarid < 120

of cycles of cropping and fallow without indicating the length of different phases of the cycle. During the early stages of shifting cultivation, when fallow periods are long, L >10. When a sedentary and permanent cultivation stage is reached, as on the compound farm, L =1. Moreover, the various systems of shifting cultivation are interwoven in the agricultural landscape. This is particularly so in Africa where traditional shifting cultivation and permanent production systems exist together in the same locality. Thus, within the general pattern of alternating fallow and cropping cycles, the exact nature of shifting cultivation varies from place to place.

Major soil types under shifting cultivation: Large parts of the humid and subhumid tropics currently under shifting cultivation and related traditional farming systems are covered by the so-called fragile upland soils. These are predominantly Ultisols, Oxisols, and associated soil types in the humid tropics, and Alfisols and associated soils in the subhumid tropics. The distribution and traits of these major soil groups are described in Chapter 15. Many of these soils are also grouped as low-activity clay (LAC) soils because of their limitations, unique management requirements, and other distinctive features that adversely affect their potential for crop production (Juo 1980). During the period from the 1970s to the 1990s, several research institutions in the tropics have been active in determining the constraints and management problems of these upland soils relative to sustainable food-crop production (Charreau 1974; Lal 1974; Sanchez and Salinas 1981; Spain 1983; El-Swaify et al. 1984). Ultisols and Oxisols have problems associated with acidity and aluminum toxicity, low nutrient reserves, nutrient imbalance, and multiple nutrient deficiencies. Ultisols are also prone to erosion, particularly on exposed sloping lands. Alfisols and associated soils have major physical limitations; they are extremely susceptible to crusting, compaction, and erosion, and their low moisture-retention capacity causes frequent moisture stress for crops. Besides, they acidify rapidly under continuous cropping, even under moderate rates of fertilizer use.

The traditional shifting cultivation with adequately long fallow periods was generally considered to be a sound method of soil management, well adapted to the local ecological and social environment. Before the forest is cleared, a closed nutrient cycle exists in the soil-forest system. Within this system, most nutrients are stored in the biomass and topsoil, and a constant cycle of nutrient transfer from one compartment of the system to another operates through the physical and biological processes of rain-wash (i.e., foliage leaching), litterfall, root decomposition, and plant uptake. For example, Lundgren (1978) reported from a review of literature from 18 locations around the tropics, that an average of 8–9 t ha^{-1} yr^{-1} litter was added from closed natural forest, amounting to average nutrient additions (kg ha^{-1} yr^{-1}) of 134 N, 7 P, 53 K, 111 Ca, and 32 Mg. The amount of nutrients lost from such a system is negligible. Clearing and burning the vegetation leads to a disruption of this closed nutrient cycle. During the burning operation the soil temperature increases, and

Figure 5.10 Intercropping under scattered *Faidherbia* trees in the West Africa Sahel. (Photo: PKR Nair)

Figure 5.11 The overstory of *Faidherbia albida* trees with a crop of millet (sorghum, *Sorghum bicolor*) underneath. The crop is nearing maturity and a new flush of leaves starts to appear on the trees indicating the beginning of the long dry season. The absence of shade cast by tree canopy during the rainy season allows the farmers to cultivate the crop right up to the base of the tree and make the best use of the improved soil fertility under trees resulting from excreta from the animals that congregate below the tree for shade the summer. (Photo: PKR Nair)

afterward, more solar radiation falling on the bare soil-surface results in higher soil and air temperatures (Lal et al. 1975). This change in the temperature regime causes changes in the biological activity of the soil. The addition of ash to the soil through burning causes important changes in soil chemical properties and organic matter content (Stromgaard 1991). In general, exchangeable bases and available phosphorus increase slightly after burning; pH values also increase, but usually only temporarily. Burning is also expected to increase organic matter content, mainly because of the unburned vegetation left behind (Sanchez and Salinas 1981; Nair 1984).

These changes in the soil after clearing and burning result in a sharp increase of available nutrients (the so-called "fertilization effect" following a fire), so that the first crop that is planted benefits considerably. Afterward, the soil becomes continually less productive, and crop yields decline because of a host of factors including soil fertility depletion, increased weed infestation, deterioration of soil physical properties, and increased insect and disease attacks. Finally, the farmers decide that further cultivation of the fields would be difficult and non-remunerative, and they abandon the site and move on to others. The abandoned site is re-invaded by natural vegetation (forest fallow). During the fallow period, the soil would regain its fertility and productivity, and the farmers could return to the site after a lapse of a few years. This cycle has been repeated indefinitely in many regions where shifting cultivation has continued for centuries, though at low productivity levels. Over a long period, as population pressure has steadily increased, fallow periods have become shorter and shorter; consequently, farmers have returned to abandoned fields before they have had enough time for fertility to be sufficiently restored (Figure 5.2). The introduction of industrial crops and modern methods of crop production has also caused a diminished emphasis on the importance of the fallow period in traditional farming practices. During the past few decades, various efforts have been made to devise ways to address the problems of soil-fertility decline caused by the shortening of the fallow phase and suggest alternatives to shifting cultivation. The most significant among such efforts is the introduction of the so-called planted fallows and improved fallows. Before discussing those efforts, let us also briefly review another traditional land-use system known as *taungya* that has many similarities to shifting cultivation.

5.3 Taungya: An Agroforestry Practice for Forest Plantation Establishment

The *taungya*, practiced primarily in the tropics especially in South- and Southeast Asia, is also considered a forerunner to agroforestry, like shifting cultivation. The word is reported to have originated, as mentioned in Chapter 1, in Myanmar (former name: Burma) and means hill (=*Taung*) cultivation (=*ya*) (Blanford 1958). Originally it was the local term for shifting cultivation and was subsequently used to describe the afforestation method; in some literature, it is described as a form of shifting cultivation. In 1856, when Sir Dietrich Brandis, the German forester who came to India at the invitation of the British government, was in Burma, shifting cultivation was widespread and there were several court cases against the villagers for encroaching on the forest reserves. Brandis realized the detrimental effect of shifting cultivation on the management of timber resources and encouraged the practice of "regeneration of teak (*Tectona grandis*) with the assistance of taungya," based on the well-known German system of *Waldfeldbau*, which involved the cultivation of agricultural crops in forests. When a plan to establish a plantation of teak using the taungya method involving local farmers was presented to him, Brandis reportedly said: "this, if the people can ever be brought to do it, is likely to become the most efficient way of planting teak" (Blanford 1958). Two decades later the system proved so efficient that teak plantations were established at a very low cost. The villagers, who were given the right to cultivate food crops in the early stages of plantation establishment, no longer had to defend themselves in court cases on charges of forest destruction; they promoted afforestation on the cleared land by sowing teak seeds. From that beginning, the practice became increasingly widespread. It was taken from Burma to Bengal in colonial India (now India and Bangladesh) and was introduced into South Africa in 1887. The practice became so popular that most of the forest plantations established in the tropical world, particularly in Asia and Africa, owe their origin to the taungya (von Hesmer 1966, 1970; King 1979).

5.3.1 An Overview of the Taungya Practice

The taungya practice is known by different names, some of which are also used to denote shifting cultivation (as listed in Table 5.1):

Tumpangsari in Indonesia; *Kaingining* in the Philippines; *Ladang* in Malaysia; *Chena* in Sri Lanka; *Kumri*, *Jhooming*, *Ponam*, *Taila*, and *Tuckle* in different parts of India; *Shamba* in East Africa; *Parcelero* in Puerto Rico; and *Consorciarcao* in Brazil (King 1979). Essentially, the practice consists of growing annual crops along with the forestry species during the early years of establishment of the forestry plantation. The land belongs to the forestry departments or their large-scale lessees, who allow the subsistence farmers to raise their food crops. An agreement is drawn up (in writing, or mostly by "mutual understanding") between the landowner (forest department) and the taungya farmer by which the farmer is required to tend the forestry seedlings and, in return, can retain a part or all of the entire agricultural produce. The agreement would last for two or three years, during which time the forestry species would grow and expand its canopy. Usually, soil fertility declines during this period, some soil is lost to erosion, and weeds infest the area, thus making crop production non-remunerative, if not impossible. Figures 5.12 and 5.13, photographs of a taungya plantation in two consecutive years in Thailand illustrate site-fertility decline.

Figure 5.12 The *Shamba* system in East Africa, a form of taungya, used for the establishment of a cypress (*Cupressus lucitanica* plantation) in Kenya. (Photo: PKR Nair 1983)

Figure 5.13 The *Taungya* system, humid lowlands, Thailand: a luxuriant-looking rice (*Oryza sativa*) crop grown in the first year of establishment of a teak (*Tectona grandis*) and *Eucalyptus camaldulensis* (not in picture) plantation. (Photo: PKR Nair 1992)

Figure 5.14 The *Taungya* system, humid lowlands, Thailand: The same field as in Figure 5.13 a year later. Note that the trees have grown taller, but the rice crop is poorer than that of the first year, with the rice plants near the trees showing signs of yellowing, the typical nitrogen-deficiency system. (Photo: PKR Nair 1993)

During the late 1970s, the first author of this book (PKR Nair) undertook a survey, as part of his first responsibilities at ICRAF, of the characteristics of the taungya system, including the nature of agreements maintained by forest departments, in Bangladesh, Burma (Myanmar), several states of India, Indonesia, Malaysia, Nepal, Pakistan, the Philippines, and Sri Lanka, as well as Kenya and Tanzania (the practice called *Shamba* in East Africa being similar to taungya). Several unpublished documents, including details of the legally binding agreements between the forestry departments and the farmers, were obtained. While discussing with the forest officials, it became evident that the norms and conditions of the agreement were enforced more by the "policing" authority of the department officials than by the terms of agreements, the poor landless farmers had no recourse to any legal procedures against the department, and, in most places, these legal agreements were note-worthy more for the violations they caused than for compliance. Over time, the laws were repealed, diluted, or ignored.

Numerous descriptive reports, mostly before 2000, are available describing different taungya practices and the growth of different plant species in the system (Aguirre 1963; Cheah 1971; Mansor and Bor 1972; Onweluzo 1979; Jordan et al. 1992); several unpublished reports and "grey literature" were also available from various institutions during the late 1970s. Research data on changes in soil fertility and other soil management aspects are, however, scarce. Alexander et al. (1980: unpublished, cited in Nair 1993) described a two-year study on the Oxisols of Kerala, India (about 10^{o}N latitude, 2500 – 3000 mm rain per year), where the greatest disadvantage of taungya was the erosion hazard caused by soil preparation for the agricultural crops. The surface horizons of the soil became partly eroded and sub-surface horizons were gradually exposed. Such studies have apparently led to the eventual abolition of the taungya practice in Kerala in the late 1980s. The addition of crop residues to the soil surface was found to be an effective way of minimizing soil loss and exposure. In an agrisilvicultural study in southern Nigeria consisting of interplanting of young *Gmelina arborea* with maize, yam, or cassava, Ojeniyi and Agbede (1980) found that the practice usually resulted in a slight but insignificant increase in soil N and P, a decrease in organic C, and no change in exchangeable bases and pH compared with sole stands of *Gmelina*. Ojeniyi et al. (1980) reported similar results from investigations in three ecological zones of southern Nigeria and concluded that the practice of interplanting young forest plantations with food crops would not have any adverse effect on soil fertility. In contrast, a study at Sapoba, Nigeria (Nwoboshi 1981) showed that intensive cultivation and cropping practiced in forest nurseries (second nurseries where the seedlings are retained for variable periods, sometimes up to three years, before they are planted out in the fields) depleted the fertility of the soil within a year or two. Although trees in the field are usually planted at 6 to 12 times wider spacings than in nurseries, the inclusion of arable crops in the plantation was reported to have effects comparable to that of frequent cultivation in nurseries in terms of soil-fertility depletion.

In the classification of taungya, a distinction is sometimes made between "partial" and "integral" (Raintree and Warner 1986, 2015). Partial taungya refers to "predominantly the economic interests of its participants (as in some kinds of cash crops, resettlement, and squatter agriculture)," whereas integral systems "stem from a more traditional, year-round, community-wide, largely self-contained, and ritually sanctioned way of life" (Conklin 1963). According to Raintree and Warner (2015), integral taungya refers to "a more complete and culturally integrated approach to rural development; not merely the temporary use of a piece of land and a poverty-level wage for labor, but a chance to participate equitably in a sustainable agroforestry economy." In other words, the concept of "integral taungya" is meant to invoke the idea of a land-use practice that offers a more complete and culturally sensitive approach to rural development.

5.3.2 Alternatives/Improvements to Taungya

The taungya system can be considered a step forward in the process of transformation from shifting cultivation to agroforestry. While shifting cultivation is a sequential system of growing woody species and crops, taungya consists of the simultaneous combination of the two components during the early stages of forest plantation establishment. Although wood production is the ultimate objective in the taungya system, the immediate motivation for practicing it, as in shifting cultivation, is food production from the component (given that taungya plantations are established on cleared forest lands and not degraded agricultural lands). In shifting cultivation, the length of the agricultural cycle can last only so long as the soil sustains reasonable crop yields. In taungya, it is primarily dependent on the physical availability of space and light based on the planting arrangements of the trees. It can be inferred from the many reports available on taungya that, in most taungya systems, erosion hazards, rather than soil fertility, are likely to pose the greatest soil management problems. The long-term effect of the practice on soil fertility will, however, largely depend on the management practices adopted at the time of the initial clearing as well as subsequent re-establishment phases. In any case, soil fertility and the related soil management practices are, perhaps, only of secondary importance in determining the continuation of the traditional taungya system. In most cases, the biological problems of continuing cropping under an expanding overstory tree canopy make it impossible to continue cropping after the initial two or three years.

Some alternatives and improvements to taungya have been attempted in different places, most of them to provide better living and social conditions for the tenants. One of the most widely quoted examples is the Forest Village scheme in Thailand (Boonkird et al. 1984). The philosophy of the scheme was to encourage and support farmers to give up shifting cultivation in favor of a more settled agricultural system, while simultaneously obtaining their services for the establishment of forestry plantations. Each farm family who agreed to take part in the scheme was provided with a piece of land of at least 1.6 ha within the selected village unit for constructing a house and establishing a homegarden. The farmers were also permitted to grow crops between the young trees in the forest plantation unit that they helped to establish according to the plans of the Forest Industries Organization (FIO). The FIO then would appoint "development teams" of multidisciplinary experts for each forest village; the teams provided agricultural, educational, and medical services to the people of the village. The scheme enabled the FIO to establish forest plantations at considerably reduced costs; during the early 1980s, there was a total of about 4,000 ha of taungya forest plantations under cultivation in the FIO scheme. Economic returns from the scheme varied depending upon various local conditions.

The concept of the forest village has been tried, with varying degrees of success, in several other countries, e.g., Kenya, Gabon, Uganda, India, Nigeria, and Cambodia. Although it was more expensive (to the forestry departments) than the traditional practice of taungya, it was particularly suitable for countries with extensive natural forest resources and large numbers of shifting cultivators and landless farmers. Ideally, the system permits sustainable use of forest land for food production by landless people who would otherwise be engaged in forest encroachment. Paradoxically, however, while the seemingly progressive approach of the Forest Village system in Thailand started getting international attention, the program and its derivative community forestry were, sort of, outlawed in Thailand consequent to drastic political changes. Some argue that the non-adoption by state foresters of the program in its original concept was what killed the Thai example of integral taungya and the Forest Village scheme (Raintree and Warner 2015).

The taungya system has been faced with bureaucratic and political hurdles. In some places, the taungya farmers would not vacate the lands at the end of the lease period, and the forestry departments stopped leasing lands to farmers anymore. In some countries, political or policy decisions were made because of increasing population pressures and other reasons to grant the taungya farmers ownership rights to the land they used to farm, and once the farmers obtained land ownership rights, they would discontinue taungya and plant homegardens or other predominantly agricultural subsistence production systems. An interesting case in point is the transformation of the *shamba* system of Kenya (Figure 5.12). That system, which is a form of taungya, was adopted by Kenya's (Government) Forestry Department in the early 1900s to establish plantations throughout Kenya. Prompted by sociopolitical considerations, the government absorbed the taungya farmers into the civil service as regular employees of the Forestry Department in 1976. Once assured of their civil-service status and benefits, they were not obliged to farm, nor would the land be allocated to them automatically (Oduol 1986).

These observations neither imply that taungya is the best form of land-use for those farmers, nor that conventional taungya should have continued forever. Despite the historical claim by forestry departments about taungya as a popular and successful agroforestry approach to establishing forest plantations, it has also been criticized as labor-exploitative. It capitalizes on the poor forest farmer's need for food and his willingness (often out of helplessness) to offer labor for plantation establishment free of cost in return for the right to raise the much-needed food crops for even a short period. The main reason that the taungya system in general and its "improvements," such as the forest village scheme of Thailand, have not been successful was that the technical and scientific foundations upon which they were based had not been adequately understood and were left to languish. Practically no research has been conducted on the biological aspects of system improvement, resulting in a lack of technical information concerning various aspects of system management. Moreover, sociopolitical factors have considerably influenced the scope and continuation of conventional taungya.

In summary, future students of agroforestry may hear about taungya as a forest plantation-establishment technique involving crop + tree combinations that foresters used for about 150 years during the height of colonialism. The system, just like colonialism itself, gradually faded and collapsed under the combined weight of its social weaknesses, administrative overreach, and political changes on the one hand, and lack of attention to technical and scientific aspects of its management on the other.

5.4 Agroforestry Pathways to Improving Shifting Cultivation: Planted Fallows

In this section, the word shifting cultivation is used in a generic sense to include also taungya and other traditional forms of the practice. As we have seen, shifting cultivation entails deliberate association of trees with herbaceous crops in simultaneous (special) or sequential (temporal) combinations. But it was considered an "ancient" and unsustainable form of land use unsuitable for meeting the demands of the modern era with increasing population pressure and competing demands for resources such as land and labor. Therefore, finding *Alternatives to Shifting Cultivation* became a popular mantra and mission for land-use experts and development professionals since the 1970s. Given that the need for finding such alternatives was a forceful push for the genesis and evolution development of *scientific* agroforestry as explained in Chapter 1, agroforestry inevitably attained a prominent bandwagon-status in such efforts. Thus, agroforestry figured prominently in the Expert Consultations on Alternatives to Shifting Cultivations organized by FAO during the 1980s (FAO 1982, 1985, 1986; FAO/SIDA 1974). Although not mentioned as a direct follow-up to those efforts, "*Alternatives to Slash-and-Burn (ASB)*" became a flagship program of ICRAF in the 1990s, with the intensification of shifting cultivation systems conceived as a central strategy of the program (Figure 5.14).

5.4.1 Fallow Intensification Pathways

Proposing an agroforestry pathway for the intensification of the swidden farming practice (another term for shifting cultivation: Table 5.1), Raintree and Warner (1986) argued that "different agroforestry options open up from different stages of intensification in swidden systems," but limited the technological proposals to a short-list of the most promising agroforestry interventions in 'main sequence' swidden systems." These included integral taungya, economically and biologically enriched fallows, variations on the 'alley cropping' theme, and various tree crop alternatives to annual cropping systems. Revisiting the pathways several years later, the authors (Raintree and Warner 2015) argued that "the original pathway diagram was offered as a conceptual tool for thinking about agroforestry alternatives, and the best use of the tool was to simplify and adapt it for location-specific purposes." Using such an approach, Linquist et al. (2004) of the Lao-IRRI Upland Rice Farming Systems Programme placed the results of their improved-fallow research in such a context. Several other such generalized graphs and presentations have been produced too; for example, van Noordwijk et al. proposed a "possible intensification pathway for jungle rubber agroforests"; Cairns (2007) presented a complex example to provide an overview of indigenous fallow technologies documented on p 20 of his voluminous book, the first of the trilogies referred to at the beginning of this chapter: *Voices from the Forest: Integrating Indigenous Knowledge into Sustainable Upland Farming*. "Economically enriched" and "biologically enriched" fallows are two other terms that are found in some literature (e.g., Raintree and Warner 1986: Figure 5.15) that refer to the inclusion of economically valuable species (such as timber trees) and nitrogen-fixing trees, respectively, in the taungya system and are also referred to as relatively more "productive" and "effective" fallows. Numerous other terms referring to various other types of planted short-term fallows became popular consequent to the promotion of the so-called "Improved Fallow" technology by ICRAF in the 1990s (see Chapter 6, Section 6.4; Table 6.9).

Based on the various descriptions of tropical cropping systems (Ruthenberg 1980; MacDonald 1982), a framework for a logical evolutionary pathway of traditional crop-production systems in the humid tropics was developed by Kang and Wilson (1987), as shown in Figure 5.16. This pathway highlights the major changes in cropping systems and indicates points at which intervention with planted fallows or other agroforestry methods could be introduced, thus preventing further resource degradation. At each of these successive stages, the length of the cropping period extends progressively and that of the fallow diminishes correspondingly. During these extended cropping periods, soil degradation continues, and the damage done cannot be repaired by the shortened fallow. Even when the most efficient soil-rejuvenation species dominate the fallow, they can only sustain yields at a level supportable by the degraded resource base. The pathway begins with a simple rotational sequence of temporal agroforestry, characterized by a short cropping period followed by a long fallow period that is long enough such that even inefficient soil-rejuvenating plant species can restore soil productivity. In this stage, the management input is low and is confined to the cropping period and the economic return to the input of labor or energy is high. In the second stage, which usually is caused by population pressure, the cropping period and the area cultivated are expanded. Returns to energy input begin to fall and management intensity increases. At this stage, there is an awareness of the contribution of the different species (i.e., soil-rejuvenating properties) in the fallow system. At the third stage, attempts are made to manipulate species in the fallow to ensure fertility regeneration in the already shortened fallow period;

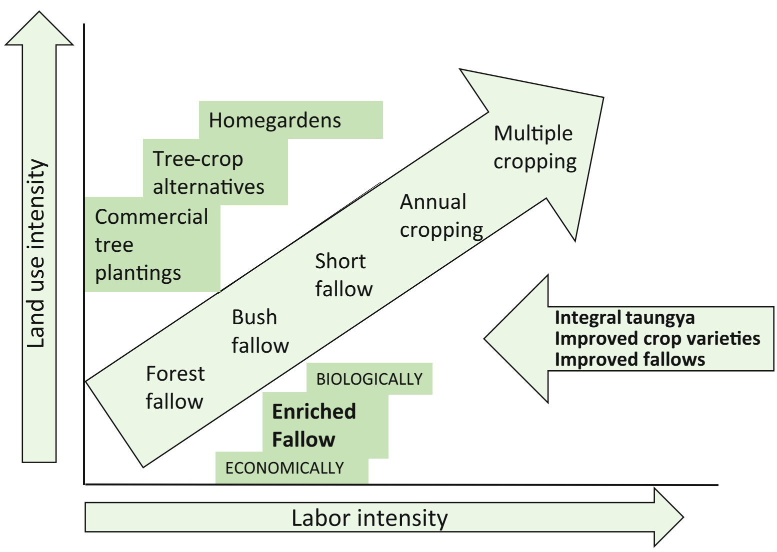

Figure 5.15 Swidden intensification pathway. Source: Raintree and Warner (1986), reproduced from Nair (1993)

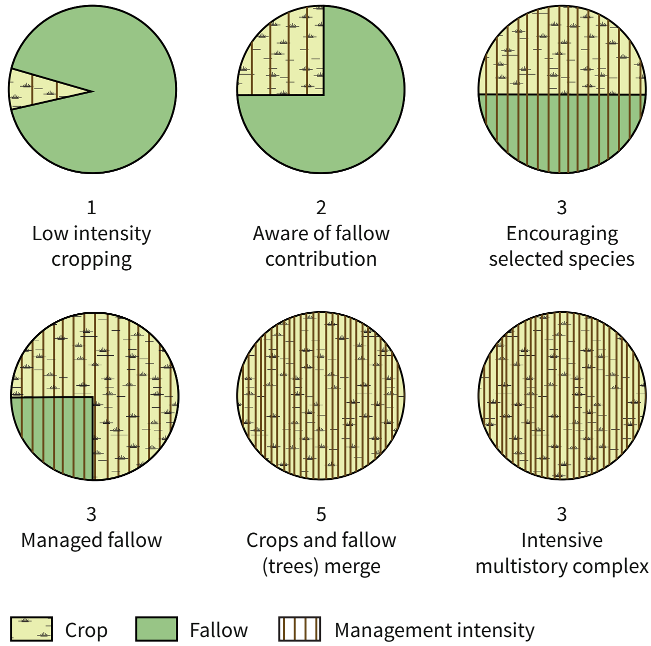

Figure 5.16 The pathways of traditional systems. (Source: Ruthenberg (1980) adapted by Kang and Wilson (1987); reproduced from the first edition of the book (Nair 1993))

a good example of this stage, taken from southwest Nigeria, is the retention and use of tree species such as *Dactyladenia* (syn. *Acioa) barteri, Alchornea cordifolia, Dialium guineense,* and *Anthonata macrophyla* as efficient soil-fertility restorers (Obi and Tuley 1973; Okigbo 1976; Getahun et al. 1982). Additionally, farmers near Ibadan, Nigeria have observed that *Gliricidia sepium*, when used for yam stakes, grew and dominated the fallow and restored soil fertility quicker than did other species (Kang and Wilson 1987). In the fourth stage, mere manipulation of fallow and sole dependence on natural regeneration for the establishment of the desired species are no longer adequate and a planted fallow of selected species becomes necessary. This is the stage at which the intervention of techniques such as alley cropping and improved fallows (Chapter 6) and *in situ* mulch (Wilson 1978) can take place. The fifth (merging of cropping and fallow phases) and sixth (intensive multistory combinations) stages could evolve from the previous stages, but there is no clear evidence for this. In many areas where multistory cropping and intensive agroforestry systems with trees and crops (Nair 1979, 2017; Michon 1983) dominate, there is no evidence of stages four and five. The most plausible explanation is that, as population pressures grow and the area available for stage three shrinks, the area for stage six (which is intensively managed homegardens where fruit trees are always among the major components) expands. As the two stages merge, the more efficient homegarden undergoes modification, which results in the development of the multistory production system.

With the above evolutionary pattern, sustainability with high productivity can be achieved when conservation and restoration measures are introduced *before* resources are badly degraded. In the humid tropics, the multistory complex, which seems to be the so-called climax of cropping-systems evolution, would be the ideal intervention at stages one or two. This may not, however, be possible in all cases, especially where different climatic and socioeconomic patterns prevail. Consequently, other types of agroforestry approaches, such as planted fallows, are necessary.

5.4.2 Planted Fallows

Early attempts to introduce planted fallows in the tropics relied heavily on the use of herbaceous legumes for production of green manures

(Milsum and Bunting 1928; Vine 1953; Webster and Wilson 1980). Later studies indicated that green manuring with herbaceous legumes was not compatible with many tropical climates, especially in areas with long dry periods which precede the main planting season (Wilson et al. 1986); most herbaceous species did not survive the dry season and thus did not have enough green matter to contribute. Herbaceous legumes such as *Pueraria phaseoloides, Centrosema pubescens, Calopogonium muconoides,* and *C. caeruleum* are widely used as ground cover in the tree-crop plantations in the humid regions (Pushparajah 1982; Nair 1988). Following the introduction of herbicides and no-till crop establishment in the tropics, some of the cover crops such as *Mucuna utilis, Pueraria phaseoloides, Centrosema pubescens,* and *Psophocarpus palustris* were found capable of producing *in situ* mulch for minimum tillage production systems (Lal 1974; Wilson 1978; Robinson and McKean 1992).

Various reports have shown that trees and shrubs, due to their deeper root systems, are more effective in taking up and recycling plant nutrients than herbaceous or grass fallows (Jaiyebo and Moore 1964; Nye and Greenland 1960; Lundgren 1978; Jordan 1985; Young 1989); this is discussed in more detail in Chapter 16. The importance of shrub legumes, including some perennials such as *Crotalaria* sp. and *Cajanus cajan,* had been recognized as early as the 1920s, and a cut-and-carry method in which leaves cut from special green-manure-source plots would be used to manure other plots on which crops would be grown had been suggested. Pigeon pea (*Cajanus cajan*) – with its deep roots – survives most dry seasons and has an abundance of litter and leaves to contribute as green manure at the start of the rains. A planted fallow of shrub legumes such as *Cajanus cajan*, already widely used by traditional farmers, was sometimes found to be more efficient than natural regrowth in regenerating fertility and increasing crop yields (Nye 1958; Webster and Wilson 1980).

With the increased use of chemical inputs, however, serious questions were raised as to whether a fallow period was needed and what minimum fallow period would sustain crop production. An objection to the traditional fallow system as illustrated in Figure 5.16 (phases one and two) is the large land area required for maintaining stable production. On the other hand, modern technologies from the temperate zone introduced to increase food production by continuous cultivation have not been successful on the low-activity clay (LAC) soils. The rapid decline in productivity under continuous cultivation continues even with supplementary fertilizer usage (Moormann and Greenland 1980; FAO 1985; Young 1989). From the results of a worldwide survey, Young and Wright (1980) concluded that, with available technology, it is still impossible to grow food crops on the soils of tropical regions without either soil degradation or use of inputs at an impracticable or uneconomic level. They further stated that, at all levels of farming with inputs, there may still be a need to fallow, or to put the land temporarily into some other use, depending on soil and climatic conditions. Higgins et al. (1982) have given some estimates of such rest periods needed for major tropical soils under various climates with different inputs. These values expressed as the cultivation factor R, which is the inverse of the land-use factor L (as explained in Section 5.2) are given in Table 5.2. The rest period needed decreases with increasing input levels.

Examples of this simple kind of rotational tree fallow are uncommon. Bishop described an agrosilvopastoral system from Ecuador, in which two years of food crops are followed by eight years of a "fallow" consisting of *Inga edulis* interplanted with bananas and a forage legume. The forage legume is grazed by pigs, and the litter from *Inga* is assumed to improve soil fertility. In Peru, biomass production from *Inga* is reported to be greater than that of a herbaceous fallow, as well as equaling or exceeding the natural forest (Szott et al. 1991). Short, sub-annual tree fallows are also possible. Tree fallow amid rice was a traditional practice in North Vietnam (Tran van Nao 1983). In northwestern India, *Sesbania cannabina*, grown under irrigation for 65 days between wheat and rice crops, added 7300 kg dry matter ha^{-1} and 165 kg N ha^{-1} (Bhardwaj and Dev 1985). In a review of the use of leguminous woody perennials in Asian farming systems, Nair (1988) identified several such examples. In most of those instances, however, the systems combine intercropping with different herbaceous crops in rotation, rather than simply alternating trees with any specific crop every season/year.

These combination cultures involving different species and components can be arranged in time and space. Traditional shifting cultivation systems are temporal, sequential arrangements where the fallow and crop phases alternate. The term "improved tree fallow" implies the use of improved tree and shrub species during the fallow phase. However, as discussed earlier, it should also involve various types of improved plant management techniques and improved plant arrangements. Depending on the local conditions, the degree of intensification can progress from a simple two-component mixture of a concomitant type, as in taungya, to space-and-time interpolated multispecies associations as in homegardens. Therefore, the term improved tree-fallow system can in practice imply improved alternatives to the fallow phase of shifting cultivation.

Most reviews on alternatives or improvements to shifting cultivation contain recommendations on tree species considered suitable as an alternate-and/or an intercrop with agricultural species. An ideal fallow species would be one that grows fast and efficiently takes up and recycles available nutrients within the system, thus shortening the time required to restore fertility. Discussions on species suitable for improved tree fallows are usually limited to trees and shrubs with soil-improving qualities. Soil improvement is undoubtedly one of the major considerations. In addition to soil improving qualities, the need for economic products from the trees also is now recognized. Thus, the ability to produce some economic products (productive role) in addition to providing intangible benefits (service role) is an important criterion. An indication of this characteristic is the addition of fruit-and-nut-producing trees to lists of potential fallow species of trees. Reviewing the tree genera and species that are suitable for maintenance and improvement of soil fertility, Young (1989) listed several species that had been quoted in earlier reviews by other workers. That list contained 31 genera and 53 species. As mentioned earlier, Nair (1988) simultaneously prepared a list of perennial legumes commonly used in Asian farming systems. Although all these species are expected to have soil-improving qualities to varying extents, many have yet to be proven scientifically. The most clearly established include those species that are primarily identified by farmers (e.g., *Faidherbia (Acacia) albida*) (Figures 5.10 and 5.11) as well as those selected and improved by scientists (e.g., *Leucaena leucocephala*). Based on the criteria of dominance in farming systems, scientific evidence, and experience-based opinions, a suggested list of trees and shrubs for soil improvement is presented in Table 5.3. Short notes on these species are included in Chapter 13, Annexure 13.I.

5.5 Concluding Remarks

Consequent to the efforts in improving shifting cultivation, the nature of the practice itself has been shifting. The traditional situation of long fallows interrupted by short cropping phases has been (or is rapidly being) replaced by shorter fallows. Present-day shifting cultivators do not (often cannot afford to) shift their residences as far apart as did previous generations because of shrinking land area per individual family and other socioeconomic reasons. Therefore, they tend to become more sedentary. This has forced them, as well as the researchers concerned about their plight, to look for land management systems by which they can get something from the land even during the so-called fallow phase. Intercropping under or between trees in fallow phases is one of the approaches mentioned as an alternative to shifting cultivation. Some prototype farming systems that would allow farmers to have continuing access to and dependence on land even during the "no-cropping" (rather than the fallow) phase as alternatives to shifting

Table 5.3 Trees and shrubs used as fallow-improvement species in shifting cultivation

Species	Preference[a]	[b]Species profile (Y/N)
Acacia mangium	2	Y
Acacia mearnsii	1	
Acacia senegal	2	
Acacia tortilis	2	
Alchornea cordifolia	2	
Albizia lebbeck	2	
Alnus spp. (*A. acuminata, A. nepalensis*)	2	
Cajanus cajan	2	
Casuarina spp. (mainly *equisetifolia*)	2	Y
Dactyladenia (syn. *Acacia*) *barteri*	2	
Erythrina spp. (*A. fusca, A. poeppigiana*)	1	Y
Faidherbia (syn. *Acacia*) *albida*	1	Y
Flemingia macrophylla	1	Y
Gliricidia sepium	1	Y
Inga spp. (*I. dulce*, *I. edulis*, *I. jinicuil*, *I. vera*)	2	Y
Leucaena leucocephala	1	Y
Leucaena diversifolia	2	
Paraserinathes (syn. *Albizia*) *falcataria*	1	Y
Parkia spp. (*P. africana, P. biglobosa, P. roxbughii*)	2	
Pithecellobium dulce	2	
Prosopis spp. (*P. cineraria, P. juliflora*)	2	Y
Robinia pseudoacacia	2	
Sesbania spp. (*S. bispinosa*, *S. grandiflora*, *S. rostrata*, *S. sesban*)	1	Y

[a]Preference for soil improvement, related to nitrogen-fixation potential
[b]"Y" indicates that short species profiles are included for the species in Annexure 13.I

cultivation have been proposed in the northeastern parts of India. But the extent to which such alternatives are adopted by the shifting cultivator will depend more on the social, economic, and anthropological conditions than on the biological merits of the suggested alternatives (FAO 1985, 1989).

Despite all these efforts, impactful improvements to the practice of shifting cultivation and in the plight of the shifting cultivator have remained elusive goals. It is infeasible to expect shifting cultivation in its traditional form (with long fallow phases) to continue; any realistic approach to improving it would have to be reconciled with a situation that demands a shorter fallow. With this realization, ICRAF focused its efforts on Improved Fallow as the desirable approach to soil fertility management for enhancing crop production in nutrient-depleted soils of sub-Saharan Africa and it became the Center's flagship program since the mid-1990s as mentioned before. Although not essentially an improvement or alternative to shifting cultivation, the program was touted as a breakthrough in improving crop production and alleviating hunger and poverty (Sanchez 1999) and it generated a lot of expectations. Major outputs and accomplishments of these massive efforts are summarized in the next chapter (Chapter 6). Overall, the results did not meet the expectations; alternatives and improvements to shifting cultivation and improvement of soil fertility to support respectable levels of crop production remain unattained goals. Given that unmanaged shorter fallows are the root cause of the disastrous consequences that are attributed to shifting cultivation, it seems logical to accept that managed permanent (sedentary rather than shifting) cultivation systems that encompass some advantages of traditional shifting cultivation would be preferable to fallow-depleted, traditional shifting cultivation. Tropical alley cropping and improved fallows were the two major efforts in this direction for about three decades (the 1980s to around 2010); those topics are considered separately in the next chapter (Chapter 6).

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6 Tropical Alley Cropping and Improved Fallows

Contents

Abstract

Alley cropping is an agroforestry practice of growing an arable crop between rows of trees or perennial shrubs. In tropical alley cropping, the perennial species, usually leguminous trees or shrubs, are planted and managed as hedgerows less than 10 m apart with the crop planted in the interspaces or alleys between the hedgerows. The trees are *pruned* at regular intervals during the cropping phase and the succulent biomass of leaves and twigs is added to the alleys as green manure (Temperate alley cropping, discussed in Chapter 10, is a form of intercropping between rows of trees where the trees are not pruned, and tree rows are spaced wider). The soil-improving attributes such as efficient nutrient recycling and soil-erosion control of the tree-based system create soil conditions comparable to those in the fallow phase of shifting cultivation. The choice of tree species is an important factor that determines the success or failure of the system. Improved Fallows was introduced as a new technology in the 1990s although its scientific basis is not different from that of tropical alley cropping: using fast-growing nitrogen-fixing trees and shrubs to support the growth and production of food crops growing simultaneously or sequentially with them. More than three decades of research and development experiences with these technologies

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have shown that they perform well under conditions of adequate water availability during crop growing seasons but are unsuitable for dry areas. Despite their technical merits, however, farmer adoption of the technologies has been low, and it is attributed to administrative failures in creating an enabling environment for providing credit and financial support, seeds and other planting materials, and strategic failures in pushing the boundaries of testing to ecological regions that are way beyond the "safe" zones for these technologies.

6.1 Introduction

Alley cropping, initially developed for tropical situations, has since been adapted to temperate zones also. However, there are differences between tropical and temperate forms of alley cropping just like there are differences between tropical and temperate forms of other land-use systems of agriculture, forestry, and animal production. In tropical alley cropping, the perennial species, usually leguminous trees or shrubs, are managed as hedgerows at distances of usually less than 10 m between rows, and the crop is planted in the interspaces or alleys between the hedgerows. The trees are *pruned* during the cropping phase to limit their height to less than a meter from the ground to reduce shading of the interplanted crop and to stimulate the growth of new foliage [*Pruning* usually refers to "trimming off the smaller branches to stimulate new shoot growth" (see Figure 14.3); however, in the context of tropical alley cropping, pruning refers to trimming off the entire upper part of the shrub]. The succulent biomass of leaves and twigs (called *prunings*) obtained in the process is used as green manure or added to the alleys. Thus, tropical alley cropping is a form of hedgerow intercropping; it is also known as "avenue cropping" in some countries. Temperate alley cropping, on the other hand, is a form of intercropping between rows of trees or "tree-row intercropping" where the trees are not pruned, and tree rows are spaced much more widely than in the tropical form to allow the use of farm machinery. Both these forms of alley cropping involve zonal (as opposed to mixed) arrangement of components, in which the components occupy definite zones, usually strips of varying widths. At least until two distinctly different words become accepted universally to denote the two forms of alley cropping, they will continue to be designated as at present (tropical alley cropping and temperate alley cropping). This chapter deals with tropical alley cropping; temperate alley cropping is discussed in Chapter 10. It needs to be strongly emphasized, however, that the random tendency to portray alley cropping as a synonym of agroforestry (for example, Wolf and DeLucia 2018) is incorrect and confusing.

6.2 Tropical Alley Cropping

In (tropical) alley cropping, the woody perennial (tree or shrub) is usually planted in single rows, but sometimes in multiple rows too, and is managed to restrict its growth in the form of a hedge. Although pruning height is variable depending on species and locations, a height of 1 to 1.5 m, which facilitates profuse branching and abundant foliage production, is generally favored. The underlying hypothesis of (tropical) alley cropping is that by retaining the trees on farmlands and adding the nitrogen-rich, easily decomposable biomass to crops grown between tree rows, the nutrients – especially nitrogen (N) – that are released through the rapid decomposition of the prunings become available to the growing crop. The pruning schedule can be set in a way to synchronize N release from the decomposing prunings with N demand of the crop at critical physiological stages (the so-called "synchrony principle": see Chapter 16, Section 16.3.3) without the risk of nutrient loss that could happen in fertilizer applications. The application of fertilizer N in quantities larger than the absorbing ability of plants leads to its loss through runoff and leaching. The soil-improving attributes (such as efficient nutrient recycling, weed suppression, and soil-erosion control) of the tree-based system will create soil conditions comparable to those in the fallow phase of shifting cultivation. Thus, alley cropping retains the basic restorative attributes of the bush fallow system of Africa (Chapter 5) and combines them with arable cropping so that all processes occur concurrently on the same unit of land; this allows the farmer to crop the land for an extended period than under the traditional bush fallow system (Kang et al. 1990). Since it combines both the cropping and fallow phases of the traditional bush fallow system, it is sometimes referred to as an "improved bush fallow system." The technique is scale-neutral, implying its suitability for conditions ranging from smallholder family farms to large-scale mechanized farming situations (Kang 1997).

The basic steps involved in setting up a tropical alley cropping configuration include:

- Plant fast-growing, preferably nitrogen-fixing, trees and shrubs, which are usually propagated by large cuttings, on crop-production fields in rows 4 to 8 meters apart (depending on the crop, one or more rows of the crop may have to be compromised for establishing the trees)
- Once the trees are established (usually 18 to 24 months after planting), prune them periodically (at 4- to 8-week intervals depending on the species and its rate of regrowth) and place or "apply" (leave on the soil surface or incorporate) the succulent foliage between rows of interplanted crops
- Let the trees grow unpruned during the dry season when there are no crops in the field
- When the land is being prepared at the beginning of the cropping season (at the end of the dry season and onset of the rainy season), cut the tree hedgerow branches that would have grown tall, strip the leaves and small branches off the thicker branches and incorporate the foliage to the soil before sowing the crop, and set aside the thicker branches for use as firewood, yam stakes, and such other farm- and household uses.
- Repeat tree pruning and application of pruning as above year after year until the trees become senile as indicated by thickening stumps and declining coppicing ability resulting in low biomass (pruning) yields, which happen when they are 10 to 15 years old depending on species. At that stage, the field could be used for other farming operations or planted with a different hedgerow species to repeat alley cropping.

Pioneering work on this technology was initiated at the International Institute of Tropical Agriculture (IITA), in Nigeria, during the early 1980s. As a newly minted technology, alley cropping generated a lot of interest among researchers and development professionals and it was portrayed as a viable alternative to the traditional bush-fallow system. The practice has been tried and evaluated in many parts of the tropics under a variety of soil- and climatic conditions (Figures 6.1, 6.2, 6.3, 6.4, 6.5, and 6.6). The technology, originally developed as an approach to enhancing crop production in areas of West Africa dominated by the traditional bush-fallow system, was soon extended to fodder production systems (by using fodder tree and shrub species as hedgerows and for erosion control on sloping lands (by using contour-aligned hedgerows as live barriers to erosion: Figure 6.7). The potential of alley cropping for reaping such benefits have been investigated under several agroclimatic

Figure 6.1 Alley cropping: *Gliricidia* - Early (1980) trials at IITA, Nigeria. (Photo: PKR Nair 1984)

Figure 6.2 Alley cropping: *Gliricidia* - Early (1980) trials at IITA, Nigeria. (Photo: PKR Nair 1985)

Figure 6.4 Alley cropping: *Leucaena* – Machakos, Kenya. (Photo: PKR Nair 1985)

Figure 6.3 Alley cropping: *Leucaena* – Machakos, Kenya. (Photo: PKR Nair 1984)

Figure 6.5 Alley cropping: *Senna siamea* – Machakos, Kenya. (Photo: PKR Nair 1985)

conditions and numerous conceptual and research-based publications on the topic were produced during the 1980s and 1990s (Kang et al. 1990, 1999; Nair 1990; Kang 1993, 1997; Akeyampong et al. 1995; Sanchez 1995; Jama et al. 1995; Cooper et al. 1966; Rao et al. 1998). Biophysical aspects were the thrust of much of the research in alley cropping; these results are summarized in this chapter.

6.2.1 Hedgerow Species

Biologically, the effectiveness of alley cropping systems depends on the tree/shrub species used – which depends on soil type and agroecological characteristics of the location – and the management strategies adopted. Several factors such as the choice of tree species, row orientation, field layout, and manipulation of the hedgerows and

Figure 6.6 Alley cropping: Acid Soil at Yurimaguas, Peru – *Dactyladenia barterii*. (Photo: PKR Nair 1985)

Figure 6.7 Contour hedgerows of *Leucaena leucocephala* for soil conservation in Haiti. (See also Chapter 18, Figure 18.17 from Haiti, and Figures 18.9, 18.10, and 18.11, and 18.12 from other countries). (Photo: PKR Nair 1988).

crop husbandry practices are important in determining the success of the alley cropping system.

The choice of tree species for alley cropping is perhaps the most important factor, and to a large extent, it determines the success or failure of the system. Kang and Gutteridge (1994) proposed several major attributes that should be considered when selecting tree species for alley cropping, including:

- fast growth rate
- ability to withstand frequent cutting
- good coppicing ability (regrowth after cutting)
- ease of establishment from seeds or cuttings
- nitrogen-fixing capacity
- deep-rooting habit
- multiple uses such as forage and firewood
- ability to withstand stresses (drought, waterlogging, soil pH extremes, etc.)
- high leaf-to-stem ratio
- small leaves or leaflets
- leaf-retention during the dry season
- non-susceptibility to pests and diseases.

A wide range of tree species has been used in alley cropping experiments or demonstrations in the tropics (Table 6.1), but *Leucaena leucocephala* (commonly known as leucaena) has been the most widely used (Kang et al. 1990). Numerous trials in different parts of humid and subhumid tropics have shown that leucaena performed comparatively better than other species in soils of relatively high base-status, whereas, in acidic, low base-status soils, leucaena was not as successful as some other species such as *Flemingia macrophylla* in Nigeria (Kang et al. 1990) and *Erythrina peoppigiana* in Costa Rica (Kass et al. 1993). Several of the species used in tropical alley cropping are used in "Improved Fallows" too as described later

Table 6.1 Common agroforestry tree and shrub species used for soil fertility improvement in Alley Cropping (AC) and Improved Fallows (IF) in the tropics and subtropics.

Species	Reported use in AC/IF	Short description	Ecological adaptability
Acacia angustissima	AC, IF	Legume, N_2 fixer; short duration; coppicing	Wide range, sub-humid
Cajanus cajan	IF	Legume, N_2 fixer; valuable grain legume, mostly short-lived; non-coppicing	Semiarid to sub-humid
Calliandra calothyrsus	AC	Legume, N_2 fixer; mildly coppicing, cattle fodder, firewood	Humid to sub-humid, Acid to neutral soils, medium elevations
Flemingia macrophylla	IF	Legume, N_2 fixer	Humid to sub-humid
Gliricidia sepium	AC, IF	Legume, N_2 fixer; fuelwood; shade tree for cacao	Wide adaptability
Inga edulis, I. jinicuil	AC, IF	Legume, N_2 fixer; coppicing	Humid to sub-humid lowlands
Leucaena leucocephala	AC, IF	Legume, N_2 fixer; vigorous coppicing, excellent cattle fodder	Basic to neutral soil, Wide range
Senna siamea	AC, IF	Legume, N_2 fixer; coppicing, fuelwood; mildly coppicing	Sub-humid to semiarid
Sesbania sesban, S. grandiflora	IF	Legume, N_2 fixer; short duration	Acid to neutral soils, Humid to subhumid
Tephrosia candida, T. vogelli	IF	Legume, N_2 fixer; non-coppicing	Acid to neutral soils, Sub-humid to semiarid
Non-Woody Species			
Calopogonium mucunoides,		N_2 fixer, short duration, green-manure/cover crop	Wide adaptability
Centrosema pubescens		N_2 fixer, short duration, green-manure/cover crop	Wide adaptability
Crotalaria spp. *(agatiflora, grahamiana, incana, striata)*		N_2 fixer, mostly short duration	Wide adaptability; dry climates preferred
Desmodium spp. *(discolor, distortum, uncinatum)*		N_2 fixer, fodder/cover crop	Wide adaptability

(Section 6.3) and indicated in Table 6.1; short profiles of some of them are also included in the Agroforestry Tree Species Profiles (Chapter 13, Annexure 13.I).

6.2.2 Nutrient (Nitrogen) Yield from Tree Species and Soil Fertility

The growing emphasis on the role of nitrogen-fixing trees in soil-fertility improvement in agroforestry systems, particularly alley cropping (Brewbaker et al. 1982; Dommergues 1987; Nair 1988), has encouraged the initiation of field trials in various places and varied conditions, and numerous research results have been published. The preponderant trend emerging from such studies is that legumes generally outperform non-legumes in terms of the productivity of the companion crops. For instance, on an Alfisol in southwestern Nigeria, Kang et al. (1999) showed that alley cropping systems involving gliricidia (*Gliricidia sepium*) and leucaena provided greater nutrient yields than those of non-legumes such as *Alchornea cordifolia* and *Dactyladenia (*syn. *Acioa) barteri,* and the former sustained moderate levels of maize yield (>2 t ha^{-1}) without exogenous nutrient inputs, implying a “saving” in the application of nitrogenous fertilizers under alley cropping situations.

There are, however, great variations in the estimates of nitrogen fixation by trees depending on methods of estimation (Chapter 17) as well as the nitrogen-fixing ability of different tree species. Given that, the nitrogen-fixation rates reported in the literature are, at best, only indicative and not necessarily accurate; but also are strictly location-specific. The nitrogen contribution of a woody perennial to a current season's crop (that usually means the amount of nitrogen made available from the decomposition of biomass added to soil and the sloughing off of legume root nodules) is the most important source of nitrogen for crops in unfertilized alley cropping systems. Obviously, the amount of nitrogen added varies, and largely corresponds to the biomass (and nitrogen) yield of trees, which in turn depends on the species and its management and site-specific factors. Simply stated, the higher the biomass yields, the greater will be the nutrient yield and cycling. As noted above, nitrogen contributions may also vary according to the rate of nitrogen fixation as well as the turnover rate of nodulated roots.

Some data on the biomass (and nutrient) yield of four woody species growing on Alfisols in Ibadan, Nigeria, under different management systems, are provided in Table 6.2. Kass (1987) reported similar data from alley cropping studies conducted in CATIE (The Tropical Agricultural Research and Higher Education Center), Costa Rica, in which *Erythrina poeppigiana* (commonly called erythrina) was grown as a hedgerow species. In one of the early reports on the topic, Torres (1983) estimated that the annual nitrogen yield of leucaena hedgerows, cut approximately every eight weeks, was 45 g per meter of hedgerow; if the hedges were planted 5 m apart, this amounted to 90 kg N ha^{-1} yr^{-1}. Higher nitrogen contributions have been reported from other field studies where the hedgerow species was leucaena or gliricidia (Yamoah et al. 1986a; Budelman 1988; Kang et al. 1999). In a comparative study of the effect of various pruning practices on leucaena, gliricidia, and *Sesbania grandiflora* (commonly called sesbania), Duguma et al. (1988) found that for all three species, the highest yields were obtained from biannual prunings at 100 cm pruning heights (245, 205, and 111 kg N ha^{-1} yr^{-1}, respectively).

The major focus of nutrient status and soil fertility studies under alley cropping was on nitrogen; however, hedgerow prunings are also reported to be an important source of nutrients other than nitrogen (Table 6.2). In studies conducted in Côte d'Ivoire, yields of 44, 59, and 37 kg of K ha^{-1} were obtained for three months from *G. sepium*, *L. leucocephala,* and *Flemingia macrophylla* (syn. *F. congesta*), respectively (Budelman 1988). Alley cropping has also been found to increase plant-available phosphorus (P), (Haggar et al. 1991; Hands et al. 1995). Other studies have shown that nutrient cycling through aboveground prunings is many times more than that which occurs through root turnover (Schroth and Zech 1995; Govindarajan et al. 1996).

The chemical aspects of soil fertility under alley cropping have received much attention in research during the 1980s to early 2000s. Based on a comprehensive review of available literature on the topic, Rao et al. (1998) concluded that the major mechanisms by which hedgerows increase or maintain nutrient status in the crop rooting zone are: (1) nitrogen input to the system through

Table 6.2 Estimated nutrient yield from hedgerow (4-m interrow spacing) prunings (not including woody material) of four fallow species grown in alley cropping on a degraded Alfisol in southern Nigeria

		Nutrient yield[a]				
	Biomass yield[a]	N	P	K	Ca	Mg
Species	t ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}				
Acioa barterii	3.0	40.5	3.6	20.4	14.7	5.4
Alchornea cordifolia	4.0	84.8	6.4	48.4	41.6	8.0
Gliricidia sepium	5.5	169.1	11.1	148.8	104.3	17.6
Leucaena leucocephala	7.4	246.5	19.9	184.0	98.2	16.2

[a]Fifth year after establishing of hedgerows; total of five prunings
Source: Kang and Wilson (1987)

biological nitrogen fixation in the case of N_2-fixing species, (2) reduced soil erosion, (3) reduced leaching loss of nutrients, and (4) uptake of nutrients from lower soil layers that are beyond the crop root zone and recycling them to the soil surface via prunings. Two aspects of this topic that received special attention were: biomass decomposition and nutrient cycling patterns, and dynamics of soil nutrient pool vis-à-vis soil chemical properties following mulch (pruning) application. These issues are of fundamental importance in hedgerow management for best results in alley cropping; both issues are considered in detail in Chapter 16.

An important criterion to judge the success of alley cropping at any location is the quantity of nutrient-rich mulch that can be produced for timely application during the crop-growing season. If the ecological conditions do not favor the production of enough quantities of nutrient-rich mulch for timely application, then there is no perceptible advantage in using alley cropping. Let us examine, for example, the quantity that could potentially be produced from 1 ha. Within a square configuration of 100 x 100 m, it is feasible to have 20 hedgerows of leucaena, each 100 m long and 5 m apart. If the hedgerows are pruned three times per cropping season (once just before the season and twice during the season), and if the rainfall conditions permit two crops a year, this results in six pruning events a year. Assuming a biomass yield of 375 g of dry matter (1.5 kg fresh matter) from each pruning per meter of hedgerow, the total biomass yield will be 4500 kg of dry matter (375 g x 2000 m x 6 cuttings). If the N content of this dry matter is 3% on average, the total N yield would be 135 kg ha^{-1} yr^{-1}, about half of which can be expected to be taken up by current season crops.

6.2.3 Soil Properties and Soil Conservation

Alley cropping, compared with annual crops, is reported to have improved soil physical conditions considerably. These include better soil aggregation, lower bulk density, and improved soil porosity, resulting in increased water infiltration and higher water holding capacity (Lal 1989; Jama et al. 1995; Yamoah et al. 1986b). These beneficial effects are primarily due to increased soil organic matter and root activity of perennial hedgerows, and secondarily due to increased activity of soil microorganisms. It is doubtful, however, if improved soil physical conditions will increase available soil water to alley crops under water-limiting conditions considering the presumed competitive dominance of the hedgerows over crops (Rao et al. 1998). An earlier study had indicated that competition for soil moisture between the hedgerows and crops made alley cropping less suitable for semiarid tracts (Singh et al. 1989).

Studies on the effect of alley cropping on other soil properties have been rare. Comparing the effect of three mulches – *F. macrophylla*, gliricidia, and leucaena – applied at the rate of 5 t ha^{-1} dry matter near Abidjan, Côte d'Ivoire, Budelman (1989) found that all three, particularly *F. macrophylla*, had favorable effects on soil temperature and moisture conservation (Table 6.3). The report by Lal

Table 6.3 Average temperature and soil moisture content over a 60-day period after adding three different mulches at a rate of 5000 kg dry matter ha^{-1}

Treatment/ mulch material	No of observations at 15.00 h	Average temperature at 5 cm (°C)	Average % soil moisture over 0–5 cm
Unmulched soil	40	37.1	4.8
Leucaena leucocephala	40	34.2 (-2.9)	7.1 (+2.3)
Gliricidia sepium	40	32.5 (-4.6)	8.7 (+3.9)
Flemingia macrophylla	40	30.5 (-6.6)	9.4 (+4.6)
LSD		1.20	1.84

Note: Values in parentheses is the difference relative to an unmulched soil
Source: Budelman (1989)

Table 6.4 Changes in some physical properties of an Alfisol under alley cropping and no-till systems at IITA, Nigeria

Cropping system	Infiltration rate at 120 min (cm h^{-1})			Bulk density (g cm^{-3})		
	Year 1	Year 3	Year 5	Year 1	Year 3	Year 4
Plow-till	24.2	23.2	21.4	1.36	1.51	1.42
No-till	18.0	12.4	5.0	1.30	1.47	1.62
Alley cropping						
Leucaena 4 m	39.8	13.0	22.2	1.26	1.44	1.50
Leucaena 2 m	13.6	22.4	22.8	1.40	1.39	1.65
Gliricidia 4 m	18.8	18.8	16.8	1.30	1.35	1.57
Gliricidia 2 m	13.8	21.0	19.6	1.33	1.45	1.55
LSD (0.1)	5.8			0.03		

Source: Lal (1989)

(1989) based on experiments at IITA indicated lower soil bulk density and penetrometer resistance and higher soil moisture retention and available plant water capacity under alley cropping compared to non-alley cropping (Table 6.4).

Soil biological activity is crucial in low-input systems where the major source of nutrient supply for crop growth is the decomposition of newly added organic residues and concomitant release of nutrients contained in them (see Chapter 16). The role of soil macrofauna, especially earthworms, is particularly important in improving soil structure and, in turn, soil water relations and nutrient availability to crops. Yamoah et al. (1986b) observed 46% higher soil microbial biomass C (a measure of biological activity) under alley cropping with gliricidia and senna (*Senna siamea;* syn. *Cassia siamea*) than under sole cropping in the 0–15 cm soil layer. Higher earthworm activity was also reported under hedgerows on Alfisols in Nigeria (Kang et al. 1990). In a 7-year trial, Hauser and Kang (1993) found nearly five times more worm casts under leucaena hedgerows (117 kg ha^{-1}) than in the middle of the alley (24 kg ha^{-1}). Similarly, higher populations of earthworms, ants, and termites were noted under alley cropping with gliricidia and erythrina in Costa Rica (Hands et al. 1995).

Reports on the long-term effects of alley cropping on soil physical and chemical properties and hence on crop production are limited to a few from IITA, the institution with the longest record of alley cropping research. Kang et al. (1989) and Kang and Wilson (1987) reported that, with the continuous addition of leucaena prunings, higher soil organic matter and nutrient levels were maintained compared to no addition of prunings. Atta-Krah et al. (1985) showed that soil under alley cropping was higher in organic matter and nitrogen contents than treeless soil. Yamoah et al. (1986a) compared the effect of senna, gliricidia, and *F. macrophylla* in alley cropping trials, and found that soil organic matter and nutrient status were maintained at higher levels with *S. siamea* (although it is not an N_2-fixing species). Another set of reports from IITA by Lal (1989) showed that over six years (12 cropping seasons), the relative rates of decline in the status of nitrogen, pH, and exchangeable bases of the soil were much less under alley cropping than under non-alley cropped (continuous cropping without trees) control plots.

Numerous field projects undertaken in various parts of the tropics have shown that contour hedgerows are an effective soil conservation measure (Figure 6.7; see also Chapter 18). Most such reports, however, are based on field observations that lack experimental rigor and therefore do not get into scientific literature (which is an important issue for many similar agroforestry studies). Apart from the review by Young (1989), which contains convincing arguments regarding the beneficial effect of agroforestry on soil conservation, two reports produced in 1989 are worth mentioning in this context. Ghosh et al. (1989) carried out a study in a 1700 mm yr^{-1} rainfall zone in southern India, with hedges of leucaena and *Eucalyptus* (species not reported) intercropped with cassava (*Manihot esculenta*), groundnuts or peanuts (*Arachis hypogaea*), and various vegetables in a field with 5% to 9 % slope; the leucaena hedgerows were pruned to 1 m at 60-day intervals after the first year. In the second year of study, the estimated soil loss from the bare fallow plot was 11.94 t ha^{-1} yr^{-1}, whereas, for the leucaena alone and leucaena + cassava, the estimated losses were 5.15 and 2.89 t ha^{-1} yr^{-1}, respectively. The other study conducted in Nigeria reported that soil erosion from leucaena-based plots and gliricidia-based plots were 85 and 73 percent less, respectively, than from plow-tilled control plots; leucaena contour hedgerows planted 2 m apart were as effective as non-tilled plots in controlling erosion and run-off. The study also showed that, during the dry season, the hedgerows acted as windbreaks and reduced the desiccating effects of the "*harmattan*" winds; soil moisture content at a 0–5 cm depth was generally higher near the hedgerows than in non-alley cropped plots (Lal 1989).

6.2.4 Crop Yields Under Alley Cropping

The criterion that is used most widely to assess the desirability and success of any agricultural technology is its impact on crop yields; alley cropping is no exception. Indeed, most alley cropping trials have reported little data other than crop yields, and that too from trials conducted over a relatively short period. The net effect of alley cropping on the various tree–crop interactions under several agroclimatic conditions expressed in terms of crop yield has been investigated/reviewed by several authors (Kang et al. 1990; Nair 1990; Kang 1993; Akeyampong et al. 1995; Sanchez 1995; Cooper et al. 1966). Rao et al. (1998) identified the major interactions that affect crop yields as those related to soil fertility, competition, weed control, and soil conservation (especially in sloping lands), and expressed the net effects of these on crop yields as presented in Table 6.5. Overall, many trials have produced promising results; but most of them have been under research conditions. Some of the results are mentioned here in the following paragraphs.

An eight-year alley cropping trial conducted by Kang et al. (1989, 1990) in southern Nigeria on sandy soil showed that using leucaena prunings only, maize yield could be maintained at a "reasonable" level of 2 t ha^{-1}, as against 0.66 t ha^{-1} without leucaena prunings and fertilizer (Table 6.6). Supplementing the prunings with 80 kg N ha^{-1} increased maize yield to over 3.0 t ha^{-1}. The effect of using fertilizer without the addition of leucaena prunings was, however, not tested in the study. Yamoah et al. (1986b) reported that to increase the yield of maize alley cropped with senna, gliricidia, and *F. macrophylla* to an acceptable level, it was necessary to add nitrogen. An earlier report by

Table 6.5 Net effect on crop yield of tree-crop-soil interactions in hedgerow intercropping systems in different climates, assuming a moderately fertile soil

Process	Semiarid	Subhumid	Humid
Nutrient availability to alleycrops	positive (S → L)	positive (L)	positive (L)
Soil chemical changes	positive (S)	positive (S)	positive (L)
Soil physical changes	positive (S → L)	positive (S → L)	positive (S → L)
Soil biological changes	neutral	positive (S → L)	positive (L)
Soil conservation	positive (S → L)	positive (L)	positive (L)
Water availability to alleycrops	negative (L)	Neutral/negative (S)	neutral
Shading	neutral	negative (S)	negative (L)
Microclimate changes	positive (S)/neutral	neutral	neutral
Weed suppression	positive (S)	positive (L)	positive (L)
Crop yield	negative (S → L)	positive (S → L)	positive (S → L)

S = small; L = large
Source: Rao et al. (1998)

Table 6.6 Grain yield of maize grown in rotation with cowpea under alley cropping at IITA, Nigeria (t ha^{-1})

Treatment†	Year						
	1979	1980	1981‡	1982	1983	1984§	1986
0N-R		1.04	0.48	0.61	0.26	0.69	0.66
0N+R	2.15	1.91	1.21	2.10	1.91	1.99	2.10
80N+R	2.40	3.26	1.89	2.91	3.24	3.67	3.00
LSD (0.05)	0.36	0.31	0.29	0.44	0.41	0.50	0.18

Note: § Plots fallowed in 1985
†N-rate 80 kg ha^{-1}; (-R) *Leucaena* prunings removed; (+R) *Leucaena* prunings retained. All plots received basal dressing of P, K, Mg and Zn
‡Maize crop affected by drought
Source: Kang et al. (1990)

Table 6.7 Grain yield and dry matter production from crops in different cropping systems at Yurimaguas, Peru

Cycle crop	Yield (kg ha^{-1}) under cropping system†							
	Cc	Ie	Nc	Fc	Cc	Ie	Nc	Fc
	Grain‡				Dry matter			
1. Maize	634a		390a	369a	1762b		2268b	4339a
2. Cowpea	778ab	526b	1064a	972ab	1972b	1791b	2597b	4766a
3. Rice	231a	211a	488a	393a	1138b	1160b	1723b	3718a
4. Rice	156c	205bc	386b	905a	929b	1151b	2121b	5027a
5. Cowpea	415a	367a	527a	352a	1398b	1353b	1404b	3143a
6. Rice		386b	382b	1557a		1054b	1037b	4897a

Note: For grain or dry matter, means within a row that are followed by the same letter are not significantly different, based on Duncan's test, $p = 0.05$
†Cc = *Cajanus cajan* alley cropping; Ie = *Inga edulis* alley cropping; Nc = nonfertilized, nonmulched control; Fc = fertilized, nonmulched control
‡Maize grain yield based on 15.5% moisture content; rice and cowpea grain yields based on 14% moisture content. *Inga* plots in cycle 1 and *Cajanus* plots in cycle 6 were not cropped
Source: Szott et al. (1991a)

Kang et al. (1981), however, had indicated that an application of 10 t ha^{-1} of fresh leucaena prunings had the same effect on maize yield as the addition of 100 kg N ha^{-1}, although to obtain this amount of leucaena leaf material it was necessary to supplement production from the hedgerows with externally-grown materials. Kang and Duguma (1985) showed that the maize yield obtained using leucaena leaf materials produced in hedgerows planted 4 m apart was the same as the yield obtained when 40 kg N ha^{-1} was applied to the crop.

Crop Yield Reductions under Alley Cropping: Results from all alley cropping trials have not always been promising, however. For example, in trials conducted on infertile acid soil at Yurimaguas, Peru (Figure 6.6), the yields of all crops studied in the experiment, apart from cowpea (*Vigna unguiculata*), were extremely low, and the overall yield from alley cropped plots was equal to or less than that from the control plots (Table 6.7). Szott et al. (1991a, 1991b) concluded from these data that the main reasons for the comparatively poor crop performance under alley cropping treatments were root competition and shading and that the competition increased with the age of the hedgerow. Other possible explanations are that the surface mulch physically impeded seedling emergence such that the decomposing mulch caused temporary immobilization of nutrients thus seriously reducing the availability of nutrients to young seedlings at a critical stage of their growth.

Moisture-stressed conditions as in low-rainfall areas form another environment where alley cropping experience has not been satisfactory.

Akyeampong et al. (1995) reviewed the results of 2- to 3-year-old experiments conducted by ICRAF in sub-Saharan Africa and found no benefit for alley-cropping at sites (50% of total sites) where rainfall was less than 1000 mm per year and concluded that under such situations, the negative effects of competition for water exceeded the positive effects of improved soil fertility. In a four-year study carried out at the International Crop Research Institute for the Semiarid Tropics (ICRISAT) near Hyderabad, India, the growth of hedgerow species was greater than that of the crops when there was limited moisture, resulting in reduced crop yields (Corlett et al. 1989; Rao et al. 1990). Similar observations have been reported from other semiarid areas too such as Kenya (Nair 1987; Jama et al. 1995). Comparing the relative performance of senna and leucaena as hedgerow species for alley cropping under the semiarid conditions (average rainfall 700 mm; bimodal distribution) at Machakos, Kenya during six cropping seasons, Jama et al. (1995) reported that maize grain yield was better when alley-cropped with senna than with leucaena (Table 6.8). Indeed, maize alley-cropped with leucaena yielded lower than under no-alley-cropping control. The results showed that senna was a better species for alley cropping than leucaena under those (semiarid) conditions, which emphasizes the importance of choosing appropriate species for alley cropping. Overall, low yields of hedgerow prunings (2 to 3 t ha^{-1} yr^{-1}) and competition for water between hedgerow species and crops were reported as the major reasons for negative yields in water-limited areas (Ong et al. 1991).

Some efforts have also been made to examine the general trends of results emerging from the numerous non-coordinated studies reported from different study locations. Reviewing the short-term results of alley cropping trials conducted on diverse soils in sub-humid and humid West Africa, Woomer et al. (1995) observed that on average (n = 44) 183% yield increase for alley-cropped maize over sole crop control. In a comprehensive analysis, Rao et al. (1998) assessed the performance of 29 alley cropping studies with no addition of nitrogen fertilizer to crops, conducted for four or more years over a wide range of soil and climatic conditions in the tropics (Figure 6.8). Experiments on sloping lands where the primary benefit is likely to be soil conservation were not included in the analysis. The tree species used were mostly leucaena (n = 12); others included senna (n = 3), gliricidia (n = 2), calliandra (n = 3), and erythrina (n = 4). Yields of sequential crops in bimodal rainfall sites are presented separately if crops involved were different (hence more than 29 observations in the figure). The results showed both positive

Table 6.8 Maize grain yield in *L. leucocephala* and *S. siamea* hedgerow intercropping systems with different hedge: crop land occupancy ratio at Machakos, Kenya. Values within a given proportion are means over the planting systems

Species	Hedge: crop land occupancy ratio	Maize yield (dry weight, Mg ha^{-1})						Average $crop^{-1}$
		1989		1990		1991		
		Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	
Leucaena	25:75	2.41	2.93	2.80	2.04	1.24	2.13	2.26
	20:80	1.82	2.61	2.94	2.13	1.05	2.50	2.17
	15:85	2.55	3.02	2.33	2.30	0.75	2.21	2.19
Senna	25:75	2.82	3.42	2.88	3.42	1.52	3.22	2.88
	20:80	2.45	3.77	2.93	3.04	1.44	2.93	2.76
	15:85	2.42	3.93	2.45	3.47	1.45	2.54	2.71
Sole maize	0:100	2.82	3.09	2.89	3.06	1.27	2.62	2.62
SED (Species at a given proportion)		0.34	0.49	0.52	0.41	0.36	0.29	0.15
SED (Proportions within a species)		0.21	0.35	0.29	0.36	0.28	0.21	0.26

Source: Jama et al. (1995)

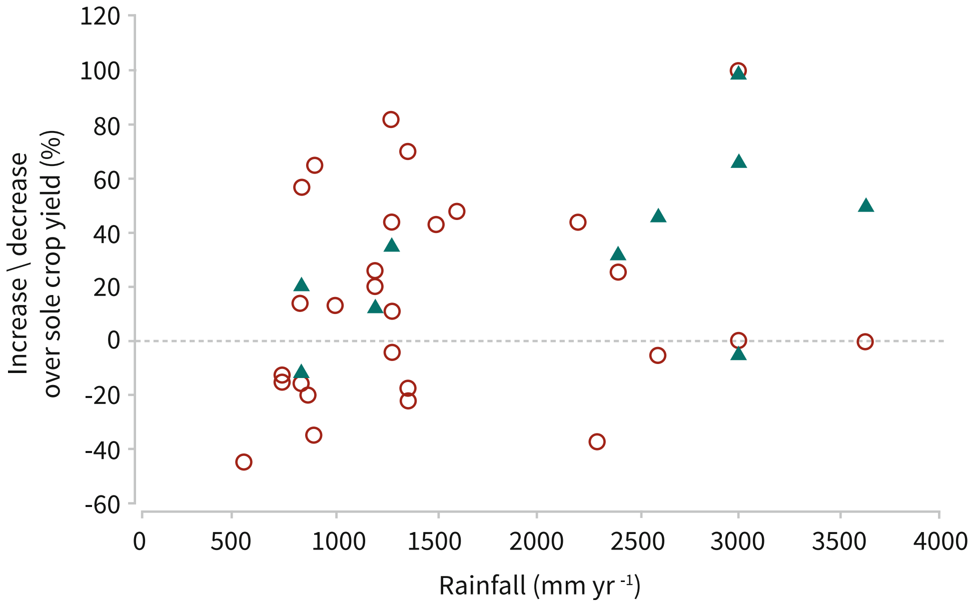

Figure 6.8 Crop yields in tropical alley cropping expressed as percent yields of same crops in sole stands in 29 experiments conducted throughout the tropics. Open circles represent the average relative yields of cereal alley crops: maize (*Zea mays*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glauca*) and rice (*Oryza sativa*). Closed triangles represent the average relative yields of non-cereal alley crops: taro (*Colocasia esculenta*), beans (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*). Source: Rao, Nair, and Ong (1998)

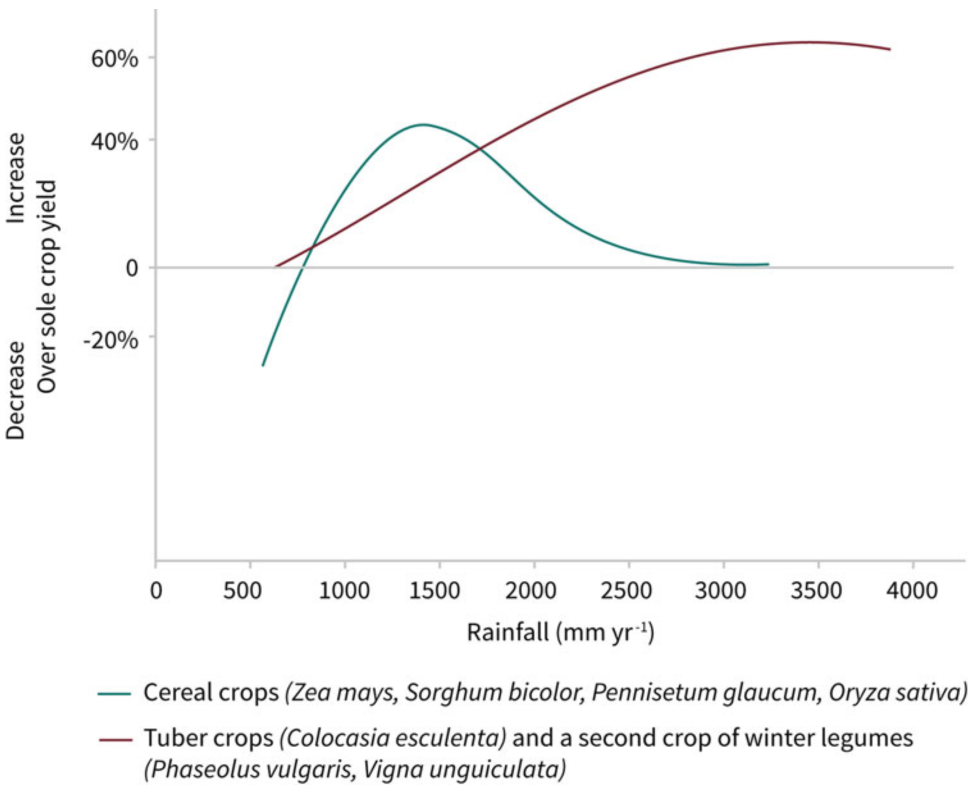

Figure 6.9 Location specificity of crop performance in tropical alley cropping: A generalized form of crop performance under tropical ally cropping showing the location specificity of annual crop response to interaction with hedge row species along productivity gradients and crop species, based on a further evaluation of the results synthesized by Rao et al. in Figure 6.8. Source: García-Barrios (2003)

(n = 15 for cereals, and n = 8 for non-cereal crops) and negative (n = 13 for cereals and n = 2 for tuber crops). Considering that yield increase of < 15% may be unattractive to farmers, only two out of 10 studies in semiarid sites with < 1000 mm annual rainfall gave any substantial crop-yield increase. In sub-humid conditions (rainfall in the range of 1000 to 1600 mm), significant positive yield responses were observed in seven out of 11 studies. In the humid tropics (rainfall > 2000 mm), the crops (maize and taro: *Colocasia esculenta*) did not benefit from alley cropping in four out of eight trials. Those results synthesized by Rao et al. (1998) were further evaluated by García-Barrios (2003), who presented in a generalized form (Figure 6.9), showing that annual crop response to interaction with hedgerow species can change strongly along productivity gradients and differs according to crop species. Thus, the yield performance of alley cropped crops is so location-specific and management-sensitive that generalizations can be difficult and misleading. Alley cropping can be advantageous in relatively fertile but nitrogen-deficient soils in the sub-humid and humid environments where there is no competition for water between the hedgerows and crops; but in semiarid areas with annual rainfall < 1000 mm and acid infertile soils, hedgerows produce too little biomass and compete with crops and crop yields are substantially reduced.

Extensive but Not Rigorous Studies? While evaluating these results it needs to be acknowledged that there have been deficiencies in the experimental procedures followed in different situations. Indeed, because of the newness of agroforestry and alley cropping as research endeavors, rigorous and uniform research protocols and procedure may not even have been established. Many of these experiments suffered from the disadvantages of small plots, in which the sole crop yields could be underestimated because of the exploitation of nutrients and water by tree roots from the alley-cropped plots. Moreover, in alley-cropping experiments, as in other woody and herbaceous mixtures, crop yields are expressed per unit of gross area, i.e., the combined area of both the hedgerows and the crops. Crop yields are measured in transects across the hedgerows, i.e., from all crop rows extending from the row closest to the hedgerow to the farthest row (Rao and Coe 1992). Studies at IITA projected maize yields with cumulative soil losses under different fallow management systems (Ehui et al. 1990). When land in fallow and land occupied by the hedgerows (in shifting cultivation and alley cropping, respectively) were considered and maize yields were adjusted accordingly to account for these possible losses (due to reduced cropping area) in production, the highest yields would be obtained if alleys were spaced 4 m apart, whereas the lowest yields would be obtained from nine-year fallow treatments. Yet another issue is the end-use of hedgerow prunings. In some situations, the biomass is used as an animal fodder instead of being returned to the soil as a source for crop nutrition and soil organic matter. A six-year study in north-western India where maize, black gram (*Vigna mungo*), and cluster bean (*Cyamopsis tetragonoloba*) were alley-cropped with leucaena and the leucaena prunings were taken away as fodder, the crop yields under alley cropping were lower than when grown in pure stands; the fodder- and fuelwood yields of leucaena were also lower under alley cropping than under non-alley cropped hedgerows (Mittal and Singh 1989).

6.2.5 The Rise and Fall of Alley Cropping

By the early 1990s, after about two decades of experience, it became evident that alley cropping as originally conceived, wherein a heavy emphasis was given to such species as leucaena, was unlikely to be a promising technology in the semiarid tropics. Several factors could limit the realization of the potential of alley cropping. A major one is soil moisture. In many semiarid regions, the rainfall is of a unimodal pattern extending over four to five months. Therefore, the number of pruning events would be reduced to about three. The mulch yield and, therefore, nitrogen contributions will also be lower, implying that the nitrogen yield will not be adequate to produce any substantial nitrogen-related benefits for the crop. Additionally, there are shade effects caused by the hedgerows as well as the reduction of land available for crop production (in a square configuration, 20 hedgerows, each casting severe shade over an area 1 m wide and 100 m long, will cover 2000 m^2 per hectare, or 25% of total area). The additional labor that is required to maintain and prune the hedges is another limitation. Furthermore, farmers may choose to remove the mulch for use as animal fodder, rather than adding it to the soil, as is the case in Haiti (Bannister and Nair 1990). While all factors related to the biological advantages of alley cropping are important, social acceptability and adoption potential of the practice are equally – even more – important. In addition to common difficulties in popularizing an improved agricultural technology developed at research stations among target farmers, some features of alley cropping counterbalance its advantages and hinder its widespread adoption. These include the need for additional labor and skills that are required for hedgerow pruning and mulch application, loss of cropping area to the hedgerows, difficulty in mechanizing agricultural operations, and potential for the hedgerow species to become a weed and/or an alternate host for pests and pathogens or harbor grain-eating birds, and possibilities for increased termite activity, especially under dry conditions.

In retrospect, alley cropping is no exception to the all-too-common experience in agricultural development initiatives in the tropics – of excessive expectations and euphoria that accompany the introduction of any new initiative, followed by disappointment when the expectations are not fully met. The reasons are several and well-known from past experiences: the craze and race for finding immediate solutions to long-standing, complex, and multifaceted problems; simplistic and trivial nature of the proposed solutions; popularization of the solution (technology) without adequate testing; and so on. Exaggerated emphasis was placed (the "panacea" syndrome) on the advantages and expectations from agroforestry, and researchers and the development community were under severe pressure to bring out something like a "magic wand" that would erase all the massive problems of deforestation, land degradation, food scarcity and poverty, and all the related issues. Alley cropping, being one of the early technologies of agroforestry, was welcomed with such a wave of extreme enthusiasm. Although it was based on a sound land-management principle – biological means of maintaining and improving soil fertility – its limitations became evident when introduced to surroundings that are unfavorable and would later be acknowledged as beyond its limits (for example, dry areas). While some proponents of alley cropping took extreme positions of going to great lengths using only positive results and ignoring the not-so-positive ones, others just denigrated and dismissed the technology. Some played it "safe" by joining the bandwagon at first lest they should be counted out of any eventual benefit, and later (when it became clear that the going was rough) trying to become smart by criticizing that it was based on weak science and posturing with the acceptance of a vague philosophical consolation that "all-results-are-valuable" (Sanchez 2019). Others, however, argue that the results of tropical alley cropping datasets need further analyses before rushing to "throw out the baby with the bathwater" (Vandermeer 1998).

The results reviewed above show that alley cropping could be promising under conditions where the annual rainfall during cropping season/s is more than 1000 mm and the soils are reasonably fertile with no serious nutrient deficiencies and extreme soil reactions. Under these conditions, alley cropping results would even be better if the land is gently sloping (less than 10% slope), and there is no labor shortage during cropping seasons. Soil-health and environmental sustainability advantages arising from reduced use of chemical fertilizers would make alley cropping a winner in such situations. An important point to remember is that under conditions where alley cropping is appropriate such as in the lowland humid tropics, the technology can be adapted for both low and high levels of productivity. If higher levels of crop productivity are the goal, fertilizer application will be necessary under most conditions. In other words, alley cropping cannot be a substitute for fertilizers if high levels of crop production are to be realized. But under conditions of adequate and well-distributed rainfall as in many humid and some sub-humid areas, fertilizer-use efficiency could be substantially increased under alley cropping compared with no-alley-cropping situations.

6.3 Improved (Shrub and Tree) Fallows

For about 15 years from the early 1980s, alley cropping was the most-talked-about and researched topic in tropical agroforestry. By the mid-1990s, that was replaced by an ICRAF-promoted technology called "Improved Fallow." It refers to "deliberate planting of fast-growing, usually leguminous, species for rapid replenishment of soil fertility, and implies the use of improved tree and shrub species during the fallow phase" (Sanchez 1995). The technology attained prominence during the early 1990s when ICRAF under the leadership of its new director-general (Pedro A. Sanchez) started focusing its institutional efforts on improved fallow as the approach to soil fertility management for enhancing crop production in nutrient-depleted soils of sub-Saharan Africa. Faced with the frustrations about the failure of alley cropping to deliver the expected benefit of the soil-improvement potential of trees and shrubs – a major scientific principle based on which ICRAF was founded – the Centre started promoting improved fallow as a breakthrough in improving crop production and alleviating hunger and poverty (Sanchez 1999). It became the Centre's flagship program since the mid-1990s and, understandably, dominated the tropical agroforestry scene in sub-Saharan Africa, and generated a lot of expectations. Numerous publications (research reports, journal articles, conference proceedings, etc.) became available during the ensuing 10–15 years; a notable one was *The Science and Practice of Improved Fallows*, a book-length compilation of mostly experiential descriptions of improved-fallows from various countries published as a special issue of the journal *Agroforestry Systems* (Buresh and Cooper 1999). The flow of publications slowed down gradually, except for a few summaries and reviews (Ajayi et al. 2007; Sileshi et al. 2008). The sections below present a brief account of these results gleaned from these publications and the author's (P.K.R. Nair) decades-long personal field experiences, observations, and interactions in sub-Saharan Africa.

6.3.1 Improved Fallow: The Practice and Terminology

As discussed in Chapter 5, fallow is a practice probably as old as agriculture itself and has been an essential component of traditional agriculture globally. Kass and Somarriba (1999) observed that fallows have been the fundamental means by which farmers in tropical America maintained sustained food production without external inputs during more than five millennia of the practice of agriculture in the region. Similar experiences have also been reported from other parts of the tropics as well as the temperate regions (Chapter 5). As a traditional low-input farming activity of smallholder farmers, the practice had several forms and variants in terms of the species used, plant-stand density, fallow length, and such other management aspects depending on local conditions. Such variations in traditional fallows are common for improved fallows too even in research trials. Thus, the literature on improved fallows is replete with several planting and management procedures and various terms to reflect these differences (Table 6.9).

Table 6.9 Fallow Terminology

Fallow: Refers to an agricultural land lying idle, either abandoned or when cropping is deliberately skipped for a season or more to give "rest" to tired land.
Natural Fallow: The early stage of secondary vegetation after a cropping period. Natural fallows, known by different terms in different places, are an essential aspect of the shifting cultivation cycles in the tropics and are dominated by weeds and secondary vegetation. Sometimes grasses of various types, especially the obnoxious weed *Imperata cylindrica* (local names: *alang-alang*, cogon grass) in the tropics and grass leys in temperate regions dominate grass fallows.
Improved Fallow: Deliberate planting of fast-growing, usually leguminous, species for rapid replenishment of soil fertility, and implies the use of improved tree and shrub species during the fallow phase.
Sequential Fallow: When the same fallow species is repeated in every fallow cycle.
Rotational Fallow: When the fallow species are different in successive fallow cycles.
Enriched Fallow: Refers to fallows that are planted with economically useful trees at low stand-densities to provide fruits, nuts, timber, and other economic products.
Managed Fallow: A term used to refer to both improved fallow and enriched fallow.
Mixed Fallow: A fallow with more than one woody species planted simultaneously on the same land during the fallow phase.
Improved fallows are sometimes referred to by the tree species used, for example "sesbania fallow," "tephrosia fallow," etc.
Although the differences among these various terms are blurry for the general reader, the experts may find "major" differences among the various terms making "lack of uniformity" an intimidating issue in comparative studies as experienced by Sileshi et al. (2008) in their meta-analysis.
Compiled from: Sanchez (1995, 1999); Buresh and Cooper (1999)

A "typical" pattern of establishing an improved fallow would be as follows:

- Seedlings of the chosen tree species are planted in the crop production field and are let to grow as a *tree fallow* for "some" time (1, 2, or 3 years) that is designated as the *fallow length*.
- If the tree species is non-coppicing (i.e., if it does not grow back after its main stem and/or branches are cut), the trees are cut down at the end of the fallow length, and the biomass (leaves, twigs, branches) is incorporated into the soil while the land is being prepared for the food crop (mostly maize).
- The food crop is raised for one, two, or three consecutive seasons (known as the *post-fallow cropping* period).
- Sometimes, incremental doses of fertilizer (25, 50, 75, 100% of the recommended levels) would be applied to the crop following the fallow (the practice is called *fertilizer amendment* in improved-fallow literature).
- After the cropping period, the cycle of fallow- and cropping-phases are repeated. Improved fallows of non-coppicing species could be *sequential fallows* (when the same fallow species is used in successive fallow periods) or *rotational fallows* (when a fallow species used in one fallow period is replaced by another species in the subsequent fallow cycle); see Table 6.9.
- Fallow species that have the coppicing ability (i.e., re-sprout after it is cut back) are left to grow for 2 years. Then they are cut back and the crop (maize) is planted every year between the stumps. These are also called improved fallows, although, in the long run, they essentially become intercropping systems (Akinnifesi et al. 2007).
- As the stump re-sprouts, the biomass is cut back two to three times during the maize cropping season and incorporated into the soil (as in tropical alley cropping).

6.3.2 Improved-Fallow Species

As mentioned above, there are two types of fallow species: coppicing and non-coppicing. The coppicing fallow species are left to grow for some time, usually 2 years, then cut back, the foliage added/incorporated into the soil, and the crop planted every year between the stumps so that the system essentially becomes intercropping or alley cropping depending on the planting pattern of the tree/shrub (fallow) species. The species used for such "fallows" are the same as those used for tropical alley cropping too (Table 6.1). Several non-coppicing species of trees and shrubs, both legumes and non-legumes, are also used in improved fallows; even some herbaceous green-manure species that have traditionally been used in agricultural systems as green-manure crops are also listed as improved fallow species in some literature. Pigeon pea (*Cajanus cajan*) that is usually grown as an annual grain legume is also sometimes used, especially its biennial cultivars, as an improved fallow species (Figure 6.10). Table 6.1 lists the essential characteristics of the improved fallow species; more detailed species profiles of some of them are included in Chapter 13, Annexure 13-I.

6.3.3 Soil Fertility and Crop Yields Under Improved Fallows

Objective assessment of the merits and weaknesses of the Improved-Fallow practice for soil fertility improvement is difficult because of several reasons. First, soil fertility improvement is hypothesized as the primary means for improving crop production through improved fallow systems, but that has often been relegated to a supporting role in attaining the goal of crop-yield increase. Therefore, the two issues are usually mixed inseparably in most reports. Secondly, the results of rigorous, process-oriented, long-term studies are not available on the topic. Moreover, the literature on improved fallows is mostly experiential (reporting experiences of specific studies) or promotional (describing its possible virtues and potential as articulations of wishful thinking without rigorous supporting evidence). Above all, there is no uniformity in the practice in terms of the species used and their management, the nature and length of fallows, and other site-specific features. The summary of available information presented below may be seen in the backdrop of these limitations.

Most of the available reports are from sub-Saharan Africa. They have indicated a significant increase in soil organic matter under planted fallows, for example, under *Cajanus cajan* on degraded soils in western Kenya (Onim et al. 1990), and under *Tephrosia candida* and *C. cajan* in Nigeria (Gichuru 1991). The review by Mutuo et al. (2005) reported increased soil C stocks in the top 5 cm soil depth by about 1.5 t C ha^{-1} within a two-year fallow with *C. cajan* and increased soil C stocks in the top 15 cm depth by about 2.5 t C ha^{-1} under a 1.5-year

Figure 6.10 Improved fallow: One-year-old *Cajanus cajan* fallow, Zambia. (Photo: Ann Degrande, ICRAF)

fallow of *S. sesban* in western Kenya. Biomass productivity data of the fallow species are sometimes used as a surrogate for soil fertility. Table 6.10 shows some such results on biomass productivity on some fallow species in Kenya used by Albrecht and Kandji (2003). Mafongoya and Nair (1997) reported that nitrogen recovery by maize from tree biomass of improved fallows was higher when biomass was incorporated in soil rather than left on the surface in Domboshawa, Zimbabwe (Table 6.11). Mafongoya et al. (2006) prepared nutrient budgets based on data for three years under non-coppicing fallows (Table 6.12). Their results showed that during the three years, while N and P budgets (stocks) were positive under *Cajanus*- and *Sesbania* fallows and fertilized maize, they were in the negative for unfertilized maize. For P, the values were positive for all treatments except for unfertilized maize, where the values were marginally in the negative (-1 and -2 t ha^{-1}). Potassium stocks, however, were in the negative for all treatments except under *Cajanus* fallow. Ajayi et al. (2007) also found similar results from a review on the impact of improved fallows in Zambia. An 8-year study showed that there was a positive nitrogen balance in the two years of cropping after the fallow for all improved fallow species. Maize fertilized

Table 6.10 Biomass productivity of some improved fallow species in western Kenya

Fallow Species	Biomass (Mg ha^{-1})		
	Aboveground	**Belowground**	**Total**
12-month-old fallows			
Crotalaria grahamiana	8.5	2.7	11.2
Calliandra calothyrsus	21.0	7.0	28.0
Cajanu cajan	8.5	3.9	12.4
Senna spectabilis	7.0	4.8	11.8
Sesbania sesban	14.2	7.3	21.5
Tephrosia vogelii	10.8	4.0	14.8
18-month-old fallows			
Crotalaria grahamiana	24.7	10.9	35.6
Calliandra calothyrsus	19.8	13.6	33.4
Tephrosia candida	31.0	33.2	64.2
22-month-old fallows			
Calliandra calothyrsus	27.0	15.5	42.5
Sesbania sesban	36.9	10.8	47.7
Grevillea robusta	32.6	17.7	50.3
Eucalyptus saligna	43.4	19.1	62.5

Source: Albrecht and Kandji (2003)

Table 6.11 Nitrogen recovery by maize from improved fallows is higher when incorporated rather than left on the surface as mulch in a loamy Ustalf of Domboshawa, Zimbabwe

Species	Quality[a]	Nitrogen recovery (%)	
		Surface applied	Incorporated in soil
Leucaena leucocephala	High	21.1ab	35.7a
Cajanus cajan	High	23.4a	30.9ab
Acasia angustissima	High	12.1c	32.4ab
Callindra calothyrsus	Low	31.3a	26.0b
Brachystegia spiciformis (Miombo litter)	low	15.3bc	13.3c
Mean values		20.6	27.7

[a]High quality = >2.5% N and <15% lignin (Palm et al. 2001)
Source: Adapted from Mafongoya and Nair (1997)

Table 6.12 Nutrient budgets for land-use systems involving non-coppicing fallows in Zambia

	Nitrogen			Phosphorus			Potassium		
	1998	1999	2002	1998	1999	2002	1998	1999	2002
Cajanus fallow	44	17	84	21	8	33	37	9	27
Sesbania fallow	47	19	110	39	24	32	–20	–25	–20
Fertilized maize	70	54	48	14	12	12	-56	–52	–65
Unfertilized maize	–20	–17	–22	–2	–1	–2	–31	–30	–38

Source: Mafongoya et al. (2006)

Table 6.13 Maize grain yield after two-year *Sesbania sesban* fallow with and without recommended fertilizer in eastern Zambia during 1998–2000 (n=48). (From Kwesiga et al. 2003)

	Maize grain yield (t ha^{-1})		
Type of land-use system	Year 1	Year 2	Year 3
Sesbania fallow + no fertilizer	3.6	2.0	1.6
Sesbania fallow + 50% recommended fertilizer[a]	3.6	4.4	2.7
Sesbania fallow + 25% recommended fertilizer[a]	3.6	3.4	2.3
Continuous maize + 100% recommended fertilizer[a]	4.0	4.0	2.2
Continuous maize + no fertilizer	1.0	1.2	0.4
LSD (0.05)	0.7	0.6	1.1

[a]Recommended fertilizer rate is 112 kg N, 20 kg P and 16 kg K per ha
Source: Ajayi et al. (2007)

with 112 kg N ha^{-1} yr^{-1} had the highest, and unfertilized maize the lowest, nitrogen balance each year (Table 6.13). An important observation was that all land-use systems showed a negative balance for potassium, the highest negative balance being in fully fertilized maize fields, possibly due to higher maize grain- and stubble yields that required a high amount of potassium and fertilizer application was only for nitrogen and, unlike nitrogen, there was no potassium contribution by the fallow species.

In Malawi, Kwesiga et al. (1999) reported *Sesbania sesban* rotational fallow increased maize yields compared to plots fertilized with inorganic nitrogen. Sanginga (2003) reported that on an Alfisol in Nigeria, leguminous tree fallows of *Cajanus cajan*, *Crotalaria grahamiana*, *Sesbania sesban*, and *Tephrosia candida* accumulated 100–200 kg N ha^{-1} between six months and two years, and biomass transfer from those species increased maize yield by four times compared with unamended controls. A report from northern Ghana showed that improved fallow with *Calopogonium mucunoides* significantly increased the yield of rice compared with natural fallows and chemical fertilizer treatments (Langyintuo and Dogbe, 2005). Similarly, an improved fallow system with *Mucuna pruriens* is reported to have increased soil organic carbon and total nitrogen under nutrient-poor conditions in the semiarid tropics of Zimbabwe (Masikati et al. 2014).

One of the comprehensive evaluations of crop-yield performance under improved fallows is a meta-analysis (using a mixed linear model) by Sileshi et al. (2008) based on a total of 94 peer-reviewed publications from West, East, and southern Africa that evaluated the yield benefits from woody and herbaceous green manure legumes. A summary of some of the main results of the analysis are presented in Table 6.14. Mean maize yield increase over unfertilized maize was highest (2.3 t ha^{-1}) and least variable (CV=70%) in fully fertilized maize, while it was lowest (0.3 t ha^{-1}) and most variable (CV=229%) under natural fallows. The increase in yield over unfertilized maize was 1.6 t ha^{-1} with coppicing woody legumes, 1.3 t ha^{-1} with non-coppicing woody legumes, and 0.8 t ha^{-1} with herbaceous green manure legumes. Doubling and tripling of yields relative to the control (Response Ratio, RR $>$ 2) was recorded in coppicing species

Table 6.14 Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Summary statistics of maize yield differences (D, t ha^{-1}) in the different treatmentss

	Full fertilizer	Coppicing	Non-coppicing	Green manure	Natural fallow
Number of publications (N)	52	10	48	54	29
Number of pairs (k)	261	185	458	622	155
Minimum	−1.3	−0.9	−2.2	−2.8	−2.9
Maximum	7.5	6.3	6.7	5.2	2.6
Mean	2.3	1.6	1.3	0.8	0.3
Mode[a]	1.4	1.2	0.2	0.3	0.2
Coefficient of variation (CV in %)	69.7	92.4	113.0	135.7	228.9
Upper quartile (75%)	3.3	2.6	2.0	1.3	0.7
Median (50%)	2.2	1.5	0.8	0.6	0.3
Lower quartile (25%)	1.1	0.4	0.2	0.1	-0.1
Percent cases with D<0 t ha^{-1}	4.6	10.3	8.3	16.2	27.1
Percent cases with D>1 t ha^{-1}	77.0	62.7	43.7	31.3	14.2
Percent cases with D>2 t ha^{-1}	53.3	35.1	23.6	12.2	0.6

[a]The mode was estimated by kernel soothing of the empirical distribution
Source: Sileshi et al. (2008)

(67% of the cases), non-coppicing legumes (45% of the cases), herbaceous green manure legumes (16% of the cases) and natural fallows (19% of the cases). Amending post-fallow plots with 50% of the recommended fertilizer dose further increased yields by over 25% indicating that legume rotations may play an important role in reducing fertilizer requirements. The authors concluded that overall the global maize yield response to legumes is significantly positive and higher than unfertilized maize and natural vegetation fallows but was still lower than that of fertilized maize. The study also showed that 3-year fallows of non-coppicing woody legumes had no advantage over 2- or 1-year fallows of non-coppicing species. The analysis also suggested that amending legume fallows with inorganic fertilizer may be important to sustain productivity over several years, as yields normally decrease with the length of post-fallow cropping period. Amending post-fallow plots with 50% of the recommended fertilizer dose could increase yields by over 25%, indicating that legume rotations may only reduce but cannot substitute fertilizer requirements. The long-recognized synergistic effect between organic and inorganic fertilizer sources was another aspect that was evident from this analysis. The main conclusions from these reports are that improved fallows, preferably of leguminous species, could have advantages in improving crop production if the soils are not extremely low in organic matter and phosphorus contents, but could lead to potassium deficiency in the long run.

6.3.4 The Rise and Fall of Improved Fallows

Improved Fallows was introduced by ICRAF as a new technology in the early 1990s. The driving force behind its development was the search for new approaches to respond to soil fertility problems, primarily of sub-Saharan Africa, resulting from the breakdown of traditional farming systems that used to have the benefit of long fallow periods. Scientifically it is founded on the well-known principles that are not very different from the foundations of tropical alley cropping that planting fast-growing tree species, especially the nitrogen-fixing ones, produce easily decomposable biomass to provide nitrogen for food crops growing together with or following the tree species, increase soil organic matter, and improve soil physical conditions. The rather disappointing performance of tropical alley cropping provided a good background and incentive for presenting the soil improvement potential of trees as the new approach to the issue.

The technology being new to sub-Saharan Africa, research testing had to be conducted on various technical issues such as species screening and selection and fallow establishment/management. While efforts on these time-consuming procedures were continuing, the technology was taken, rather prematurely, to the dissemination stage based on its assumed promise and success potential. A noteworthy aspect of the technology development, however, was the realization that the success of such technologies crucially depended on their suitability to local conditions that could best be realized by farmers' participation in technology development and adaptation. Consequently, farmers were involved in assessing technology and making modifications based on their experiences. For assessing the extent of farmers' adoption of the improved fallow technology, farmers who planted trees for a second cycle were identified as "adopters" as opposed to those still in the first cycle of tree fallows, who were described as "users." Presenting the case study of Zambia, Ajayi et al. (2007) describe how the scaling up of the technology to different parts of the country was coordinated by a Network comprising representatives of ICRAF, government research and extension services, farmer organizations, and nongovernmental organizations (NGOs). From less than a hundred planters in the early 1990s, the number of farmers who planted improved-fallow trees reportedly increased each year by tens of thousands of farmers. Subsequent reports indicated, however, that the initial euphoria fizzled out and the number of adopters declined gradually to the extent that out of the nearly 700,000 smallholder farmers who were reportedly planting improved fallows in East and Southern Africa, only less than 50,000 (7 percent) continued to do so after four years. The major reason for the failure of the adoption of the technology that was acclaimed as "rock-solid" was attributed to the lack of a financial package to offset the opportunity costs for one or two years (Sanchez 2019). Strangely, however, the same author has attributed the failure of tropical alley cropping – the scientific foundation of which is basically the same as that of improved fallow – to the weakness of its science (". . . decades of research devoted to an agroforestry technology without fully taking into account the principles . . .")!

6.4 Concluding Remarks

In conclusion, what lessons can be learned from three decades of efforts in agroforestry technology development involving soil-improving trees and shrubs?

- Both alley cropping and improved fallows are two sides of the same coin; the scientific principles of both are fundamentally the same (although this is not unanimously accepted)
- Both technologies perform well under conditions of adequate water availability during crop growing seasons but are unsuitable for dry areas
- The artificial dichotomy between the two technologies perpetuated by some researchers should be eschewed and efforts should be focused on finding the best ways of incorporating the proven benefits of including fast-growing woody legumes and other species in smallholder farming systems of nutrient-poor tropical soils.
- It seems that the low level of adoption of the technologies by the targeted clientele of smallholder farmers of sub-Saharan Africa is due to two major reasons: 1. Administrative failures (in creating an enabling environment for providing credit and financial support, seeds and other planting materials, "fertilizer amendment" as needed, etc.), and 2. Strategic failures in pushing the boundaries of testing to ecological regions that are way beyond the "safe" zones for these technologies.

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Tropical Homegardens

7

Contents

Abstract

Agroforestry homegardens consist of multispecies combinations of a variety of economically useful plants including trees, shrubs, vines, and herbaceous species, often grown in association with livestock, in small landholdings around or adjacent to the home. These unique farming systems founded on generations of experience and traditional knowledge provide sustenance to billions of households in the humid and subhumid tropics and subtropics. Several types of homegardens have been identified according to their differences in size (area), form, layout, zonation pattern, species composition, management objectives, and the dominant plant species or the level of urbanization.

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Some of the well-known homegardens, known by their locations, include those of Kerala (India), Java (Indonesia), Kandy (Sri Lanka), Chagga (Tanzania), Central America, and the Amazonia (Brazil), each with its unique historical as well as contemporary characteristics. Their enormous species diversity, which consists of food crops, medicinal plants, ornamentals, fruit trees, multipurpose trees, and fodder species, contributes to a variety of ecosystem services, and supports food-, and nutritional-, and livelihood security of millions of tropical smallholder farmers. Homegardens are also found in the temperate regions, but only to a limited extent in area and complexity compared to the tropics. Research on homegardens has mostly been limited to inventory and characterization of species diversity and descriptive accounts of ecosystem services. In the era of increasing emphasis on the market economy and yield maximization, the homegardens are not only being "ignored and left behind" but are also being transformed from their traditional subsistence outlook to market-oriented production enterprises.

7.1 Introduction

The term homegarden is used in agroforestry literature to denote a distinct form of land-use that represents one of the oldest forms of traditional land management in many tropical countries. Agroforestry homegardens should not be confused with ornamental gardens around homes, written as "home gardens" (two words).

Homegardens consist of multispecies combinations of a variety of economically useful plants including trees, shrubs, vines, and herbaceous species, often in association with livestock, in small landholdings around or adjacent to the home; photographs of two homegardens, one from Sri Lanka, and the other from Samoa are included as Figures 7.1 and 7.2, respectively. Considered a "time-tested example of sustainable agroforestry" (Kumar and Nair 2006), these unique farming systems founded on traditional knowledge systems and experiences acquired over generations have provided sustenance to billions of households in the tropics. In the humid- and sub-humid tropics where the homegardens are predominant, they account for a

Figure 7.1 A "typical" rural homegarden from Sri Lanka. (Photo: Focali: Forests, Landscapes and Livelihood research network – www.focali.se)

Figure 7.2 A multistory agroforestry homegarden in Samoa (Pacific Islands). The major species include *Artocarpus altilis* (breadfruit), *Cocos nucifera* (coconut), *Flueggea macrophylla* (bushweed), *Musa* spp. (banana/plantain), *Theobroma cacao* (cacao) and *Morinda citrifolia* (noni). (Photo: Craig Elevitch)

major share (up to 70% by some estimates) of contribution by smallholder farming systems to food production (see Chapter 8, Section 8.3; Chapter 23).

7.2 Global Distribution of Homegardens

Homegardens are most widespread in the tropics but can be found elsewhere too; a global distribution map is presented in Figure 7.3. South- and Southeast Asia; the Pacific islands; East-, West-, and Central Africa; the Caribbean and the Pacific Islands, and Mesoamerica are the major regions where tropical homegardens are common (Nair and Kumar 2006). Highly populated Java (population density: 1172/km^2: BPS 2018), Indonesia, and Kerala (population density: 860/km^2; https://www.census2011.co.in/census/state/kerala.html), India, are considered the two "hotspots" of tropical homegardens. In Java, the homegarden agroforests are estimated to cover about 20% of the arable land. In Kerala, it is critical to the local subsistence economy and food security for about 5.4 million small gardens (mostly less than 1.0 ha in area). Homegardening is also common in Central America, Amazonia, tropical and subtropical parts of China, the Mediterranean region of Catalonia, and many parts of Africa (Figure 7.3). *Streuobst*, a traditional multispecies gardening practice in several parts of Europe, is somewhat similar to tropical homegardening; see Chapter 10, Section 10.4.2: Herzog 1998). Indeed, EURAF (The European Federation of Agroforestry: see Chapter 10) has adopted the

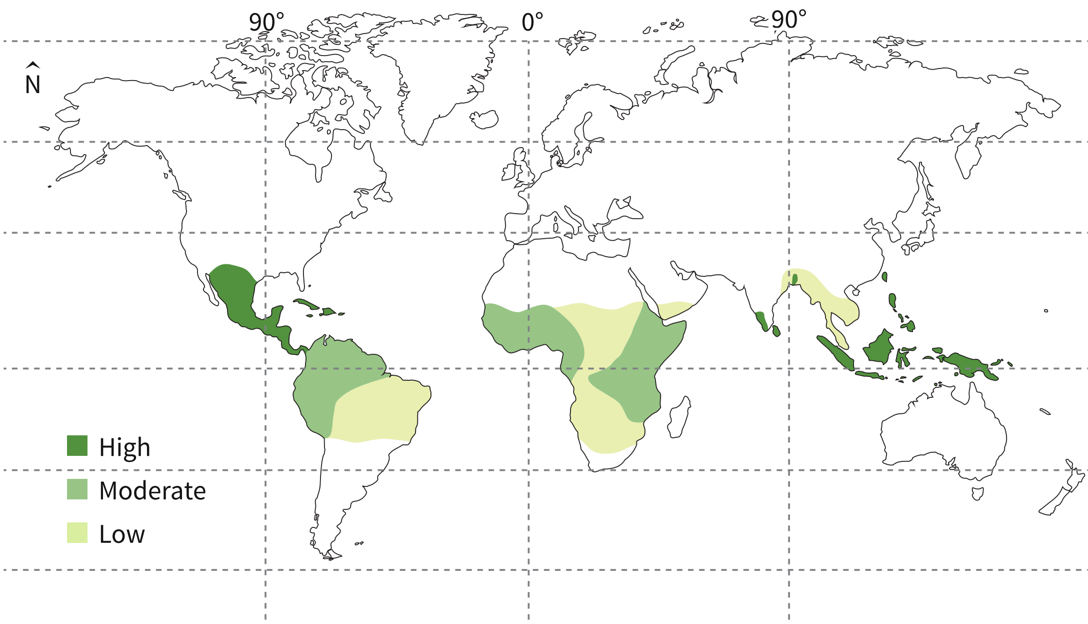

Figure 7.3 The global distribution of homegardens (Redrawn/Reprinted/Adapted by permission from Springer, Nair and Kumar (2006). European literature lists Homegardens as one (out of the five) of the major forms of agroforestry practices (see Chapter 3, Section 7). Some practices, described as *Streuobst* [Herzog (1998)] are also similar

term kitchen gardens as the synonym for homegardens and recognized it as one of the five agroforestry practices in Europe (Chapter 3, Section 3.8; Table 3.4). Although predominantly a rural practice, homegardening is gradually being extended to urban and peri-urban settings (see Section 7.4), with a commercial orientation (Nair 2006; Al-Kofahi et al. 2019). Despite the long history of economic and socio-cultural importance of homegardens for rural livelihood in many parts of the tropics, our understanding of the science underlying the practice is incomplete.

7.3 History, Evolution, and Distribution of Homegardens

Concrete evidence is not available on how, when, and where this land-use system originated. Archeological evidence from central India dating back to the Mesolithic period (10,000 to 4,000 BCE = BC) indicates that products from 63 species of fruit plants including *Phyllanthus emblica* (syn. *Emblica officinalis*), *Mangifera indica*, *Ficus* sp., *Madhuca* sp., and *Ziziphus* sp. were consumed (eaten raw, ripe, roasted, or pickled) by the local inhabitants (Randhawa 1980). Literary evidence also suggests that homegardening in South Asia probably dates back to as early as 5,000 BCE (*cf.* Puri and Nair 2004). According to Wiersum (2006), homegardening was associated with the fishing communities inhabiting the moist tropical regions in Southeast Asia and it originated between 13,000 to 9,000 BCE, whereas Soemarwoto (1987) reported that the earliest available evidence of homegarden cultivation in Java, Indonesia, was around 3,000 BCE. Miller et al. (2006) suggest that the homegarden history in Amazonia corresponds with the evolution of agriculture and domestication of trees in ancient times, followed by the development of cultural complexes along the Amazon River and its main tributaries.

From the pre-historic and dispersed origins, homegardens have gradually spread to many humid and sub-humid regions especially in South- and Southeast Asia including Java (Indonesia), the Philippines, Thailand, Sri Lanka, India, and

Bangladesh. Suggesting the preponderance of homegardens in prehistoric India, Vatsyayana in his classical book – *Kamasutra* – a masterpiece of Sanskrit literature, written *ca*. 300 to 400 CE (= AD), portrays *house gardens* as a source of green vegetables, fig trees (*Ficus* spp.), mustard (*Brassica* spp.) and many other vegetables (*cf.* Randhawa 1980). Furthermore, Randhawa (1980) stated that early travelers (e.g., Ibn Battuta, Persian traveler: 1325–1354 CE) described homegardens with coconut (*Cocos nucifera*), black pepper (*Piper nigrum*), ginger (*Zingiber officinale*), sugarcane (*Saccharum officinarum*) and pulses (grain legumes) in Kerala, India, in the early 14th century. Natural history studies in southern India during the late 1800s to early 1900s also suggest that societies habitually used their homesteads for a variety of needs such as food, energy, shelter, and medicines (Kumar and Nair 2004). Michon et al. (1983) allude that tree gardening systems were already widespread on the Indonesian island of Java in the tenth century CE.

Parallel to geographical expansion, the homegarden system has also evolved through successive generations of perpetual intensification of cropping in response to rising demographic pressure and the resultant scarcity of arable lands. In this context, the garden owners are often viewed as "perpetual experimenters" as they are persistently trying and evaluating new species, varieties, and technologies (Niñez 1987). A fresh species may be selected by the gardener because of its value in terms of food, wood, energy, medicinal, religious, ornamental, and based on self-instinct or knowledge passed on by kin and neighbors. This process eventually may have led to the development of complex multistory production systems in many parts of the tropics. Both the Javanese homegardens of Indonesia and the Kerala homegardens of India, the two prominent types of homegardens have seemingly developed over centuries of cultural and biological transformations and they represent the accrued wisdom and insights of farmers who have interacted with surroundings, lacking exogenous inputs, capital, or scientific skills (Kumar and Nair 2004). Socio-culturally also, agroforestry homegardens fit well with the prevailing farming systems and traditional village lifestyles, making it socially acceptable.

Homegardening is regarded as the earliest method of plant domestication. Domestication of fruit trees and tuber crops may have corresponded with one another as the hunter-gatherers used to collect both fruits and tubers from the forests. Gradually, however, the accidental dissemination of seeds became more purposive with key species planted to ensure their usufructs (Wiersum 2006). It is also probable that the prehistoric people may have impulsively selected trees with larger fruit size, better quality, or other desirable features from the wild, besides assisting in their regeneration. This, in turn, led to the cultivated populations becoming genetically distinct from their wild progenitors (Ladizinsky 1998).

While such "improvements" were occurring in the suite of cultivated species, the indigenous communities, over millennia, also interfered with the natural ecological processes of the forests in their subtle and persistent ways. For example, the pre-Columbian and contemporary Amazonian peoples managed the forest resources through practices such as species selection, tending, care, and management, thus promoting patches of domesticated forests around human settlements with one or a few useful species (Levis et al. 2018). This presumably must have given rise to the notion of "forest gardens," which is sometimes used synonymously with homegardens, as mentioned in the following section. Wiersum (2004) described forest gardens as "reconstructed natural forests, in which wild and cultivated plants coexist, such that the structural characteristics and ecological processes of natural forests are preserved, although the species composition has been adapted to suit human needs."

7.4 Types of Homegardens

Homegardens are known by various terms such as agroforestry homegardens, household or homestead farms, compound farms, backyard gardens, village forest gardens, dooryard gardens, and house gardens (Table 7.1). Some local names

Table 7.1 Homegarden terminology

Terms	Regions where it is predominantly used
Agroforestry homegardens	Most tropical and temperate countries
Backyard gardens	
Compound farms	
Dooryard gardens	
Homegardens	
Homestead farms	
House gardens	
Household gardens	
Kitchen gardens[1]	
Forest gardens or Village forest gardens[2]	Sri Lanka; Southeast Asia
Talun-Kebun[3]	Indonesia
Pekarangan[4]	
Shamba[5]	East Africa
Chagga homegarden[6]	
Huertos Familiare[7]	Mesoamerica
Food forests or Edible forest gardens[8]	Caribbean islands; Europe; North America
Streuobst[9]	Europe

[1]Vegetable cultivation areas adjacent to the kitchen
[2]Forest gardens or Village forest gardens are "intermediate" land-use systems in the nature-culture continuum and are defined as "reconstructed natural forests, in which wild and cultivated plants coexist, such that the structural characteristics and ecological processes of natural forests are preserved, although the species composition has been adapted to suit human needs" (Wiersum 2004)
[3]Rotational system between mixed gardens and tree plantations of Java
[4]The famous Javanese homegarden intercropping systems.
[5]A form of "taungya where agricultural crops are grown together with forest tree species, widespread in the high-potential areas of Kenya since the early 1900s" (Oduol 1986)
[6]A multi-storeyed cropping system practiced by the Chagga tribals on Mt. Kilimanjaro, Northern Tanzania
[7]Local name for homegarden systems in Mesoamerica
[8]Food forests are "low-maintenance and low-input agroforestry systems, characterized by a wide diversity of plant species" including fruit and food trees and also nonfood perennial hardwood trees (Beckford and Campbell 2013)
[9]A traditional system involving "tall trees of different types and varieties of fruit, belonging to different age groups, which are dispersed on cropland, meadows and pastures in a rather irregular pattern" (Herzog 1998) – similar to homegardens

such as *Talun-Kebun* and *Pekarangan* that are used for various types of homegarden systems of Java (Indonesia), *Shamba* and *Chagga* in East Africa, *Huertos Familiares* of Central America, and forest gardens in Sri Lanka, have also gained international acceptance because of the remarkable systems they symbolize. Although the nature and arrangement of components of the homegardens vary in different places depending on local ecology and socio-cultural traditions, they all represent complex, multispecies land-use systems that are intensively managed by the homeowner throughout the year for a variety of products that are mostly used for household consumption and sustenance. Figures 7.4 and 7.5 illustrate the diversity of species found in the homegardens of Kerala in southern India, and Jamaica in the Caribbean, respectively, which are just but two examples of the multispecies, multistory canopy configurations of tropical homegarden systems.

In general, differences in size, form, layout, zonation pattern, species composition, and management objectives abound in the homegardens. Accordingly, several homegarden types have been recognized, which generally reflect differences in size (area) of gardens and the dominant plant species or the level of urbanization. Based on zonation, diversity, total garden area, and socioeconomic functions, Mendez et al. (2001)

Figure 7.4 A multistory homegarden in Kerala, India. The ubiquitous coconut palms (*Cocos nucifera*) are a prominent component of the Kerala homegardens and are grown in association with several annual and perennial species of different forms; see also Chapter 8. (Photo: BM Kumar)

Figure 7.5 A multistory homegarden in Jamaica: Breadfruit trees (*Artocarpus altilis*) occupies the top tier of this multistrata canopy arrangement with cacao (*Theobroma cacao*), avocado (*Persea americana*), and other medium-tall trees in the next lower canopy tier. Below that layer are plantains (*Musa* spp.), papaya (*Carica papaya*), and similar other fruit plants. Fodder grasses (*Panicum* sp.), pineapple (*Ananas comosus*), and short-statured annuals such as tuber crops occupy the lowest canopy floor along the plot boundary. (Photo: PKR Nair)

attempted a cluster analysis to designate homegarden types. They recognized six types of Nicaraguan homegardens: ornamental, handcrafting (providing space and shade for handicraft manufacturing), subsistence, handcrafting and mixed production (for consumption and income), mixed production, and minimal management. Wiersum (2006) suggested four types of homegardens: survival, subsistence, market, and budget gardens. Based on a Hierarchical Ascendant Correspondence Analysis, Caballero-Serrano et al. (2016) grouped the Amazonian homegardens into three categories: small (recent), medium (established), and large (transitional) gardens. Proximity to urban centers is yet another criterion used to classify the homegarden systems into *urban* (within city limits), *peri-urban* (places on the fringes of urban areas), and *rural* (village) types. Some authors reported that the homegardens located near the urban centers contain fewer species and a larger number of ornamental and commercial plants than those in rural areas, implying that the focus of urban homegardens is more on provisioning services, e.g., production of marketable fruits, vegetables, and other edible products (Clarke et al. 2014). The urban homegardens unlike their village counterparts are also usually smaller in size. In general, the distinctions among the garden types mentioned above are somewhat fuzzy and such categorizations are arbitrary.

7.5 Ecology and Structure

Ecologists consider homegardens as "steady-state" systems, where photosynthetic production matches respiratory losses, i.e., inputs balance outputs, with structural attributes analogous to those of natural forest ecosystems (Kumar and Nair 2004). Selected ecological characteristics of homegardens concerning those of agricultural and forest systems are presented in Table 7.2, indicating the similarities between homegardens and natural forest ecosystems. Homegardens, especially of the so-called forest-garden type, which represents the "intermediate land-use systems in the nature-culture continuum" (Wiersum 2004), could resemble young secondary forests both in structure and total biomass store and may be considered as a man-made forest kept in a permanent early-successional state (Jensen 1993).

Homegardens are time-honored examples of sustainable agroforestry. Kumar and Nair (2004) described it as "the epitome of sustainability in managed land-use systems," implying that it is perhaps the most sustainable among all managed land-use systems. Their remarkable species- diversity, closed nutrient cycling, and low "nutrient export" through harvested products are the major traits that impart sustainability to these systems. Unlike monospecific production systems, homegardens combine the ecological functions with the socioeconomic welfare of the landowners, implying both ecological and socioeconomic sustainability. Ewel (1999) described such land-use systems "structurally and functionally the closest mimics of natural forests yet attained," while Nair (2017) deems the managed multi-strata tree + crop systems in the tropics (e.g., coconut-palm-based multispecies homegardens and shaded perennial systems) as an "agroecological marvel".

7.5.1 Floristic Diversity

A prominent structural attribute of tropical homegardens is the great diversity of species ranging from herbaceous plants to climbers and tall trees, consisting of food crops, medicinal plants, ornamentals, fruit trees, multipurpose trees, and fodder species (Table 7.3). Based on surveys in over 400 homegardens (with a total area of 45.2 ha) in southwestern Bangladesh, Webb and Kabir (2009) recognized as many as 419 species (59% native, 51% trees and shrubs) – of which six were on the IUCN Red List for Bangladesh[1]. Enormous variations also exist in homegarden species within and across regions, making each garden a unique entity (Kumar and Nair 2004). Many factors contribute to such

[1] The IUCN Red List – https://www.iucnredlist.org – provides the most comprehensive inventory of threatened biological species in the world.

Table 7.2 A comparison of the ecological attributes of climax forests, homegardens, and conventional agricultural systems (monocropping)

Parameter	Natural climax vegetation	Homegardens	Conventional agric. systems
Biogeochemistry	Nutrient inputs equal outputs	Inputs and outputs balance each other	Outputs far exceed inputs
Biotic stress	Low	Low	High
Canopy architecture	Multistrata	Multistrata	One- or two-layered
Disturbance regimes	Rare (except natural disturbances, such as tree fall)	Intermediate	High
Diversity	High	Intermediate	Low
Ecological succession	Normally uninterrupted; reaches a stable climax-stage	Consciously manipulated	Arrested, beyond the early stage
Entropy	Low	Low to high	High
Floristic spectrum	Shade tolerant and intolerant	shade tolerant to intolerant	Mostly shade-intolerant
Input use	No external inputs;	Low	High
Site quality	Progressive improvements (e.g. facilitation)	Progressive improvement	Steady decline
Standing biomass/net primary productivity (NPP)	Highest among the terrestrial ecosystems (mean NPP: 2000 g m^{-2} $year^{-1}$)	Comparable to climax formations, but NPP estimates are lacking (standing biomass stock in Kerala homegardens: 32.6 to 71.6 Mg ha^{-1}, Kumar 2011)	Low (mean NPP: 650 g m^{-2} $year^{-1}$; Leith 1975)
Sustainability	High	Medium to high	Low to medium

Source: Adapted from Kumar and Nair (2004)

Table 7.3 Commonly reported plants in homegardens of humid tropical lowlands

Category	Species in homegardens
Root and tuber crops	*Colocasia esculenta* (taro), *Dioscorea alata* (greater yam), *Dioscorea esculenta* (sweet yam), *Ipomoea batatas* (sweet potato), *Manihot esculenta* (cassava), *Xanthosoma* spp. (tannia or cocoyam)
Other food crops	*Ananas comosus* (pineapple), *Arachis hypogaea* (peanuts), *Cajanus cajan* (pigeon pea), *Passiflora edulis* (passion fruit), *Phaseolus, Psophocarpus* and *Vigna* spp. (beans and other legumes), *Saccharum officinarum* (sugarcane), *Zea mays* (corn = maize), and various vegetables
Fruit and nut yielding perennials	*Anacardium occidentale* (cashew nut), *Annona* spp. (soursop and sweetsop), *Averrhoa carambola* (carambola), *Artocarpus heterophyllus* (jack fruit), *A. altilis* (breadfruit), *Carica papaya* (papaya), *Citrus* spp.(lemon, lime, orange, tangerin), *Cocos nucifera* (coconut), *Ficus* spp. (edible figs), *Mangifera indica* (mango), *Musa* spp. (bananas and plantains), *Persea americana* (avocado), *Psidium guajava* (guava), *Spondias dulcis* (vi apple, hogplum), *Syzygium malaccense* (Malay apple), *Tamarindus indica* (tamarind)
Spices, Social beverages, and stimulants	*Areca catechu* (betel nut), *Cinnamomum zeylanicum* (cinnamon), *Curcuma longa* (turmeric), *Cymbopogon citratus* (lemon grass), *Piper betle* (betel vine), *Piper methysticum* (kava), *Zingiber officinale* (ginger).

Source: Adapted from Nair (2006)

variations, the most important being the preferences of gardeners and the size and age of the gardens. Each species within a garden is chosen to fulfill a specific function or an ecosystem service (e.g., food, wood, medicinal, religious, ornamental values). The introduction of new species may also occur at any time of the year (Yamamoto et al. 1991), depending on the specific properties/uses of the species in question, and regardless of whether they are native or exotic. Serrano-Ysunza et al. (2018), in a longitudinal study on agrobiodiversity changes in homegardens of Tabasco, Mexico, found that species that disappear at some periods may reappear with time.

Some reports are available on the relationships between the number of woody species and the homegarden's size and age (e.g., Tolera et al. 2008). The direct relationship between the size of the garden and woody species richness (total number of species) is understandable because larger areas available allow the landowner to grow more species. However, the relationship between the age of the garden and species richness is more complex. The term age of the garden by itself is difficult-to-explain unless the garden is of the "first-generation" type, i.e., established directly after forest clearance. Tolera et al. (2008) determined the age of crop fields and homegardens since conversion from the natural forest using a chronosequence approach based on information from key informants combined with interpretation of aerial photographs of the area. Kumar (2011) reported, however, that while the woody species richness of homegardens within a region may increase with the size of the holding, the scenario will be different when the species richness is considered on a unit area basis. As shown in Figure 7.6, the total species (plant)

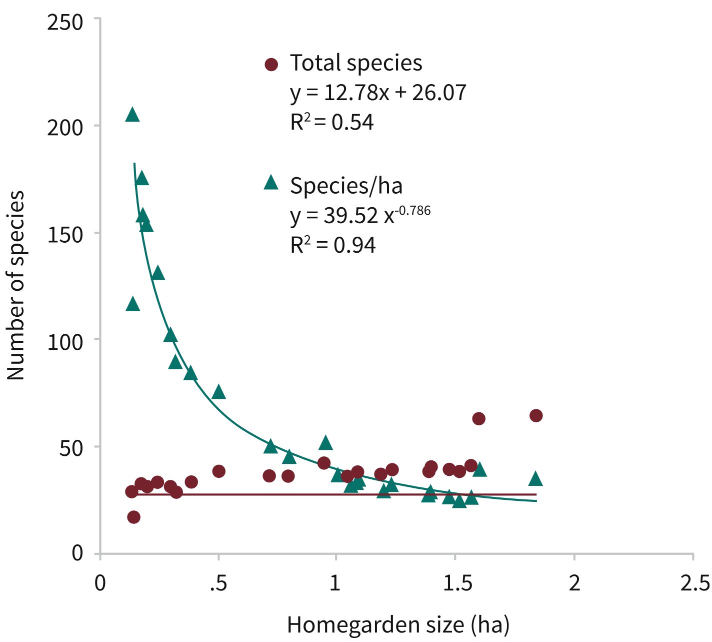

Figure 7.6 The relationship between species richness and the size of homegardens in Kerala, India. Species richness is the number of species, or simply a count of the botanical species; it does not represent the abundance of the species. In the figure, "Total species" means the total number of species (botanical) in a garden, and "Species/ha" means the number of botanical species per ha (estimated by dividing the total number of species per garden by the size of the garden and extrapolating to a hectare-basis). Note that although the total number of species per garden is somewhat similar between the smaller (< 0.5 ha) and larger (>1.0 ha) gardens, the total number of species per hectare is much more in the smaller gardens than in the larger gardens. Source: Adapted from Kumar (2011) with permission from Elsevier

count or richness expressed on a unit area (hectare) basis was considerably higher in smaller gardens although the total number of botanical species (on a unit-area basis) is somewhat similar between the smaller (< 0.5 ha) and larger (>1.0 ha) gardens. This shows that owners of the small homegardens grow a wide spectrum of plants at higher planting density compared to owners of the larger homegardens. Increased plant density as well as diversity may be the smallholder farmers' strategy to maximize total farm production.

Species composition of homegardens depends both on its position in the overall farming system and the livelihood strategies of the farmers (Wiersum 2006). Specific needs and preferences of the household and nutritional complementarity with other major food sources, besides ecological and socioeconomic factors, are key processes in this respect. Das and Das (2015) suggested that factors such as proximity to urban areas, market access, and geographical and social isolation, besides the size of the homegardens play a major role in determining the diversity of homegardens. Other socioeconomic and sociocultural aspects such as ethnicity, education level, gender, occupation of the owners, and biophysical attributes such as altitude may also impact homegarden floristics. Another important factor that influences species diversity is the intensification of agricultural production and the associated introduction of species with high commercial value, especially near urban centers. Proximity to urban centers and the propensity of farmers to introduce species with high commercial value are generally regarded as drivers of the homegarden diversity decline phenomenon.

A shift from subsistence agriculture to market economy often underlies homogenization (i.e., transformations generally aimed at simplified cropping systems) of the homegarden structure and increased use of external inputs (Kumar and Nair 2004). Homogenization of agricultural landscapes owing to commercial simplification is a widespread concern in many parts of the world. Indeed, Abebe et al. (2013) observed that the introduction of new cash and annual food crops into the homegardens of southern Ethiopia "could jeopardize the integrity and complexity of the system, which has been responsible for its sustenance." Societal processes of rural transformations and globalization, therefore, may alter homegarden floristics and their contribution to agrobiodiversity conservation (Serrano-Ysunza et al. 2018). Such changes in homegarden species composition and richness are sometimes viewed as reflections of the homegardeners' ability to continuously refine and adapt their livelihood strategies and preferences in the wake of quick social, economic, and cultural transformations of rural territories (e.g., Zimmerer 2007; Buchmann 2009; Hecht 2010).

Another remarkable attribute of the homegardens is the great diversity of *landraces* and cultivars that highlight intraspecific variability of species. In a study on Amazonian Dark Earth homegardens (see also Chapter 20, Section 20.6.1), Junqueira et al. (2016) reported that the farmers recognized different landraces for 33 species, and some species such as banana (*Musa* spp.) had as many as 20 landraces, signifying the existence of enormous diversity at the intraspecific level in the homegardens of Amazonia and elsewhere. Moreover, homegardens are reported to help conserve many rare and endangered species (Watson and Eyzaguirre 2002; Gunawan et al. 2004). Webb and Kabir (2009) suggested that the profound variability in homegarden floristic richness across sites and regions generally indicates that "under some circumstances tropical homegardens exhibit high levels of plant diversity and serve as a repository for rare and threatened species." The complex vegetation structure of homegardens may also provide habitat for different bird species (Parikesit et al. 2004) as well as wildlife (Perfecto and Vandermeer 2008). Overall, tropical homegardens are splendid illustrations of maintaining species diversity in cultivated and managed landscapes.

7.5.2 Vegetation Structure

Vegetation structure refers to the arrangement of various floristic elements of the gardens and the age- or size-class distribution of the woody components. Two aspects of structure are often recognized: vertical (i.e., how the tree and crop strata are vertically oriented) and horizontal (i.e., how the various components of the garden are placed or zoned laterally). Indeed, the structure and composition (diversity and the nature of components involved) of homegardens are tightly interrelated and influenced by numerous socioeconomic and biophysical factors. The multi-tiered and judiciously managed canopy architecture (Figures 7.4 and 7.5) is perhaps the most distinguishing feature of humid tropical lowland gardens. Most authors delineate a three-to-six-strata system, with about three quarters to full ground coverage (Kumar and Nair 2004; Mohri et al. 2018). The vertical stratification provides a gradient in light and relative humidity, which produces diverse niches allowing many species assemblages to flourish, with the shade-tolerant species occupying the lower stratum, shade-intolerant trees in the upper layer, and species with varying degrees of shade tolerance in the intermediate levels. Variations from this general pattern of multi-tiered canopy architecture also exist. For example, in the Mediterranean (Catalonia, Spain) and the arid tropical (Soqotra island, Yemen) gardens, stratification is typically restricted to a lower stratum of herbs and shrubs and a higher one of trees (Agelet et al. 2000; Ceccolini 2002). The Vietnamese *Vuon-Ao-Chuong* system (VAC or Garden-Pond-Livestock pen systems) is another case in point with a simple vertical structure (Mohri et al. 2018). Garden age and management are cardinal factors that impact the vegetation structure. Older gardens, regardless of size, may evolve a multistrata canopy structure, while younger gardens may have a simpler vertical stratification.

Discrete horizontal zonation patterns also occur in the homegardens, and their position, extent and species composition reflect careful managerial approaches. For example, the Javanese and Kandyan homegardens not only exhibit a complex horizontal zoning but also a multilevel vertical structure with a variety of species (Mohri et al. 2013). The number of such management zones per homegarden is also variable: it may range from two to six, with a mode value of three (Kumar and Nair 2004). In general, food- and fruit-producing species dominate the zone adjoining the residential quarter and working areas, and small plots of annual crops separate this part of the garden from the more distant parts usually allocated to woody perennials. Medicinal and ornamental species are typically cultivated in small areas or pots surrounding the house, and vegetables in areas adjacent to the kitchen. Multipurpose tree and shrub species used as live fences are usually planted on farm boundaries regardless of holding size. Trees also may be scattered throughout the homestead or at specific points to offer or elude shade, essential or detrimental to various plants, besides providing support for climbers (e.g., *Piper nigrum*). Plants that are included in different zones generally mirror the farmer's management priorities and socio-economic needs. Possibly, a large number of species are planted in distinctive patterns unique to each homegarden to optimize space, light, water, and fertilizer requirements. On another note, while an archetypal homegarden may characterize a delineated area (fenced-in or bounded by field risers), often it is not easy to differentiate the homegarden boundaries from the adjoining arable cropping area (Figures 7.7, 7.8, and 7.9).

7.5.3 Ecosystem Services

The role of agroforestry systems in providing a range of ecosystem services is well recognized; the nature and extent of such services provided by different agroforestry systems including homegardens are discussed in Section V of this book, Chapters 19–22. Briefly, these include various provisioning services such as the production of food, fuel, fodder, medicines, ornamental plants, green manure, and timber resources; regulating services including the maintenance of soil fertility, erosion control, watershed protection, and microclimate modification, as well as the provision of shade and fencing, pest regulation, pollination, and climate and environmental resilience; and cultural services such as aesthetics, recreational and spiritual values. The most significant

Figure 7.7 Terraced rice fields in the foreground and coconut-dominated homegardens in the background in Bali, Indonesia. (Photo: Craig Elevitch)

Figure 7.8 Rice in the foreground with a multistory homegarden consisting of various short and tall species in the elevated field behind the rice field in Bangladesh. (Photo: PKR Nair)

Figure 7.9 Homegarden-rice paddy continuum – Vietnam. (Photo: ICRAF/Southest Asia, and Prasit Wangpakapattanwong, FAO)

role of homegardens, however, is in ensuring food and nutritional security for millions of tropical smallholder farmers who are the major practitioners of homegardening; these issues are discussed in Chapter 23.

7.6 Commercialization of Homegardens

Commercialization refers to the production of crops for sale in the market rather than for household consumption. While the traditional homegardens mostly represent smallholder production systems of the subsistence or non-commercial type, large homegardens with a higher proportion of commercial crops have also become common lately. Adoption of input-intensive, new technologies to maximize productivity is an intrinsic feature of the commercial systems. This, in turn, has transformed many traditional (subsistence) homegardens into production systems that are designed primarily to meet the need for more cash income. For example, commercialization has caused a decline in the structure and functions of the Indonesian *pekarangan* and *talun-kebun* systems (Abdoellah et al. 2006). Commercial gardens are characterized by lower species diversity and a greater number of plants (usually of the same species) per garden (Table 7.4; see also Section 7.5.1). Consequently, a few plant species dominate such homegardens, which may gradually acquire the characteristics of monocultures. Examples include the gardens containing commercial crops such as vegetables that are in high demand in urban markets of West Java, Indonesia (Abdoellah et al. 2006). Mellisse et al. (2018) reported that transition

Table 7.4 Plant diversity parameters in commercial and non-commercial homegardens in Sukapura village, West Java, Indonesia

Structural attributes	Commercial homegardens (n = 35)	Non-commercial homegardens (n = 59)
Area (m^2)		
Average	461.5	270.7
Range (min.–max.)	120–2000	85–1400
Number of species		
Total	145	181
Average	15.71	15.37
Range (min.–max.)	4–49	4–41
Number of all plants		
Average	1227	66
Range (min.–max.)	95–8388	6–159
Shannon–Wiener diversity index		
Average	1.11	2.03
Range (min.–max.)	0.16–2.00	0.96–3.12
Pielou's evenness index		
Average	0.42	0.78
Range (min. –max.)	0.07–0.86	0.39–0.95

Source: Adapted from Abdoellah et al. (2006). For the vegetation survey, the authors randomly selected 94 households out of 3433 and recorded the species name, number of individuals of each species per plot/farm, number of structural layers based on plant height, and the plant category based on the main use (Vegetable, Ornamental, Food, Fruit, Spices, Medicinal, Building material and other species). Homegardens were defined as "commercial" (if more than half of the products from the homegarden were sold for cash) or "non-commercial" (if more than half of the products were consumed by the family). Cash crops such as vegetables were usually found in the lowest layer (less than 1 m tall; 88.6% of the total). "Range" under "Number of all plants" represents the total number of plants per garden

Table 7.5 Annual dry matter yield of different crops, farm-level energy productivity of food crops, and total revenue for the different homegarden systems in southern Ethiopia

Homegarden systems	Total crop yield (annual dry matter kg ha^{-1})	Energy productivity of food crops (GJ ha^{-1})	Revenue (US\$ ha^{-1})
Khat-based (n = 18)	$2438^{b} \pm 427$	$20^{b} \pm 8$	$6817^{a} \pm 1842$
Enset-cereal-vegetable (n = 9)	$3021^{a} \pm 813$	$21^{b} \pm 6$	$1675^{b} \pm 567$
Enset-based (n = 9)	$2864^{ab} \pm 426$	$43^{a} \pm 17$	$719^{c} \pm 346$
Enset-coffee (n = 18)	$1817^{c} \pm 372$	$17^{b} \pm 7$	$1763^{b} \pm 843$
Enset-livestock (n = 9)	$2540^{b} \pm 701$	$20^{b} \pm 7$	$2368^{b} \pm 1305$

Khat = *Catha edulis*, Enset = *Enset ventricosum* and coffee = *Coffea arabica*
Values in cells represent mean followed by standard deviation (n = 63). Means with different superscripts within a column are significantly different between homegarden types at $P < 0.05$
Source: Adapted from Mellisse et al. (2018)

from the traditional enset (*Enset ventricosum*) + coffee (*Coffea arabica*) homegarden systems to *khat* (*Catha edulis*)-based and enset-cereal-vegetable systems (commercial) in the southern highlands of Ethiopia has led to a decline in livestock herds and a shift from organic manure to inorganic fertilizer use. Despite this, the latter two systems (i.e., *khat*-based and enset-cereal-vegetable systems) showed better productivity and provided better food security than the traditional enset-coffee systems (Table 7.5), partly because of the superior purchasing power it offers to the owners of such gardens. Wiersum (2006) describes that such changes in homegarden characteristics may mirror the quest for a new equilibrium in the relationship between urban and rural areas. On the other hand, others (e.g., Parikesit et al. 2004) perceive such changes as a loss to traditional characters of the system that are rooted in history and culture and demand the need for revitalizing them.

7.7 Major Tropical Homegarden Systems

As mentioned, species composition, management practices, age structure, and size of homegardens are profoundly variable, even within a region, making each garden a unique entity. As a result, the homegardens of different geographical regions show considerable variations. But multi-functionality, multi-tiered canopy architecture, complementary resource use, agrobiodiversity conservation, predominantly subsistence nature of the system, and the role of women in land management are the underlying principles that bind them. Some of the prominent homegarden systems around the world are briefly described in the ensuing section.

7.7.1 Homegardens of Kerala (India)

As stated, the southern Indian state of Kerala is one of the two "hotspots" of tropical homegardens. Although homegardening is popular elsewhere in India too, particularly the eastern and north-eastern regions, the Kerala homegardens have become more widely known. Since time immemorial, these multifunctional homegardens have continued to be a ubiquitous feature of Kerala's landscape. Despite the drastic changes in the land-use patterns in Kerala since the mid-1900s, the homegardens are still important for providing subsistence and cash returns to farm families. The coconut palms form the dominant, central component occurring in 97% of the homegardens, and other components – both perennial and annual species – are integrated with the palms (Nair 1983, Jose and Shanmugaratnam 1993; Fox et al. 2017). Other common tree crops in the gardens include commercial species such as the areca palm (*Areca catechu*) and Para rubber tree (*Hevea brasiliensis*). Banana, jackfruit (*Artocarpus heterophyllus*), mango (*Mangifera indica*), and other multipurpose trees are also important components.

7.7.2 Javanese Homegardens of Indonesia

The Javanese words *Pekarangan* (homegarden) and *Talun-kebun* (bamboo-tree gardens) are often used synonymously with the word homegarden. Just as in the case of Kerala homegardens, the Javanese homegardens are legendary, centuries-old constituents of the rural ecosystems in Java and involve a mixture of annual and perennial plants harvested on a daily or seasonal basis. According to ancient records, homegardens of Java started as community spaces linked to temples, palaces, and homes (Mohri et al. 2018). Homegardening is popular elsewhere in the Indonesian archipelago too (e.g., Sumatra). With the government-policies to promote transmigration of families from the heavily populated Java to other islands, the Javanese homegardens are being "replicated" in other regions of the Indonesian archipelago by the Javanese peasant settlers.

Apart from their economic and ecological functions, the homegardens also play important social and recreational roles in rural societies. For example, the Javanese homegarden is an important locale for socialization with family, friends, and neighbors (Soemarwoto 1987). In Java, homegardens and bamboo-tree gardens are an important status symbol too. People who do not have a homegarden are generally not ranked high in social esteem. The homegardens also play an important role in the inheritance system of the Javanese society; being a family asset inherited through generations, such gardens are seldom alienated (Parikesit et al. 2004).

Damar agroforests of Sumatra: The damar (*Shorea javanica*) agroforests of Sumatra and elsewhere in Indonesia are a variant of the homegarden system (Figure 7.10). The farmers have established these forest gardens by planting damar trees in upland swidden rice fields. The damar tree yields a resin, locally known as *damar mata kucing* in Sumatra. It is used in the production of incense, varnish, paint, and

Figure 7.10 Damar (*Shorea javanica*) agroforestry gardens in Sumatra, Indonesia. (Photo: E. Torquebiau)

cosmetics. Traditionally, the resin used to be collected from the damar trees in the natural forests. However, as the wild resources were dwindling, attempts were made to establish damar gardens. Kusters et al. (2008), while describing the system, stated that it is "a showcase win-win example of a land-use system with both economic and environmental benefits". Harvest of resin from damar trees constitutes the principal source of household cash income (see also Chapter 11, Section 11.5.9).

7.7.3 Polynesian Homegardens

Homegardens are pervasive in the Pacific island landscapes, from the very densely populated urban areas in atoll microstates, such as South Tarawa, Kiribati, Fogafale Islet on Funafuti Atoll, Tuvalu, and RETA in northeast Majuro Atoll, Marshall Islands to rural villages and plantations in areas of low population density in Fiji, Vanuatu, and Papua New Guinea (Thaman et al. 2006; Elevitch 2007, 2011). They generally involve an array of food trees, non-tree staple and supplementary food plants, medicinal plants, and other non-food trees and plants of cultural and commercial significance (Figures 7.2 and 7.10). As in other homegarden systems, ornamental plants, medicinal and aromatic plants, sacred plants, and other culturally valuable multipurpose plants, are common components of the system.

Agrodeforestation (loss of tree cover from the agricultural landscape) has been a critical problem in the urban and peri-urban areas of these islands (Thaman et al. 2006). The principal drivers for exacerbating the problem include rising population pressure, poverty, and the need for fuelwood; expanding squatter settlements; nonexistence of rules for regulating tree removal; increasing dependence on root crops such as cassava and sweet potatoes (*Ipomoea batatas*); and the loss of traditional knowledge on the importance of trees in the context of rapid urbanization. In the rural areas, promotion of a wide range of export cash crops (e.g., coconut, banana, cacao (*Theobroma cacao*), sugarcane (*Saccharum officinarum*), coffee (*Coffea* spp.), ginger (*Zingiber officinale*), and butter pumpkin (*Curcurbita maxima*) has led to clearing of diverse agroforests (Thaman et al. 2006).

7.7.4 The Shamba and Chagga Gardens of East Africa

The *Shamba* and *Chagga* are two types of traditional homegardens that are popular in East Africa. The *Shamba*, which is also considered a form of *taungya* system (Chapter 5, Figure 5.12), involves growing agricultural crops together with forest tree species; it used to be widespread in the high-potential areas of Kenya, but is less popular now. The *Chagga* homegardens, on the other hand, are still widespread on the slopes of Mt. Kilimanjaro, especially on the upper southern slopes. These gardens have been nurtured by the *Chagga* tribe for more than a century. Much like the other homegarden systems, the *Chagga* homegardens are also located close to family dwellings (Figure 7.11). Just as the Javanese homegardens (Section 7.7.2), the *Chagga* gardens play important social and recreational roles too apart from their economic and ecological functions (see Chapter 22, Figure 22.7). The gardens mostly involve cultivation of perennial crops such as banana and coffee, and some annual crops such as maize (*Zea mays*) and beans (*Phaseolus vulgaris*). Trees and shrubs are planted both on the farm boundaries and as scattered trees inside the homegardens. A. Hemp (2005a) and C. Hemp (2005b) have reported that the typical feature of the *Chagga* homegardens is their multilayered vegetation structure similar to a tropical montane forest with trees, shrubs, lianas, epiphytes, herbs. The boundary planted trees are also intensively lopped and pruned (Chapter 11, Figure 11.4). Livestock such as cattle and goats form an integral part of the garden, which are usually stall-fed (Fernandes et al. 1984; Fernandes and Nair 1986; Hemp 2005a, 2005b; Ichinose et al. 2020). The crop residues and tree leaves serve as feedstock for livestock, and the animal dung, feed residues, and crop residues are recycled as organic manures – the only source of soil nourishment in the homegardens and other smallholder farm production systems of Africa (Zingore et al. 2007; Ichinose et al. 2020). The conversion of these traditional homegarden areas into maize production has become widespread since the 1990s following the crash in coffee

Figure 7.11 The *Chagga* homegardens in the foothills of Mt Kilimanjaro, Tanzania are a unique homegarden system. (Photo: Andreas Hemp)

prices in the international markets (Soini 2005), an oft-cited example of a shift in the land-use dynamics of the traditional homegardens as a function of market forces.

7.7.5 The Sri Lankan Homegardens

Homegardens account for about 14.8% of the total land area in Sri Lanka and provide approximately 42% of the country's wood and wood products (FAO 2009). A subset of the Sri Lankan homegarden is the *Kandyan* homegardens (Figure 7.1), which originated in the historical *Kandyan* Kingdom and the adjoining regions. As elsewhere, the Sri Lankan homegardens are smallholder production systems providing a multiplicity of goods and services. These multistrata systems, involving associations of annual and perennial crops, livestock, and occasionally fish, function as a supplemental source of food and income for households at low input costs daily. According to Mattsson et al. (2018), homegardens in Sri Lanka, "are the poor farmers' insurance and safety-net in dire food situations, giving additional nutrition and calories". Several governmental programs in Sri Lanka, therefore, have incorporated homegardening as a key element to support food and nutritional security. Besides, homegardens figure prominently in Sri Lanka's Intended Nationally Determined Contributions (INDCs) to the United Nations Framework Convention on Climate Change, UN REDD+ program to reduce emissions from deforestation and forest degradation and the National Adaptation Plan for Climate Change (NAP) 2016–2025 (Mattsson et al. 2018).

7.7.6 Central American Homegardens

The Mayan civilization, which practiced sustainable agriculture for centuries, involving many indigenous crops and soil protection approaches, evolved in Mesoamerica. Within this region in the Mayan domain, diverse native groups, descendants of the ancient Maya, established multi-strata homegardens to fully exploit the available solar radiation. Montagnini (2006) has acclaimed them as the world's most diverse homegardening system. This region is also heavily populated; poverty and malnutrition co-exist both in the urban and rural areas. The Mesoamerican homegardens also exhibit widely varying vertical and horizontal structure and species composition (Rico-Gray et al. 1990). Conventionally, households establish several agricultural subsystems such as "milpa" (outfield extensive slash and burn agricultural areas), homegardens, beehives, irrigated orchards, and hunting areas. Furthermore, the Mayan lowland orchards and homegardens have been considered crucial for the semi-intensive production of commercial crops such as cacao, annatto (*Bixa orellana*), and vanilla (*Vanilla planifolia*) during the 16th and 17th centuries (Castro et al. 2018). In recent decades, however, owing to the social and economic changes in the Yucatan Peninsula (Mexico) caused by tourism, improved roadways, and expanding urban centers, the Mayan homegardens are undergoing major changes (Martínez-Ballesté et al. 2006).

7.7.7 Homegardens in the Brazilian Amazon

Homegardens constitute a dominant land-use system in the Brazilian Amazon since time immemorial. Recent archeological studies have indicated the importance of polycultures (homegardens) in the pre-Columbian land use of eastern Amazon (Maezumi et al. 2018). Indeed, the adoption of polyculture agroforestry – combining the cultivation of multiple annual crops with progressive enrichment of edible forest species and the exploitation of aquatic resources – was associated with the development of complex societies in the Amazon region, as early as ~4,500 years ago. This legacy of pre-Columbian land use on the modern vegetation composition of Amazonia, however, has been a source of debate for long. Some authors argue that the hyper-dominance of edible plants in the modern forests of eastern Amazon presumably is an enduring legacy of the persistent anthropogenic landscapes for the past 4,500 years (ter Steege et al. 2013). Anthropological and ethnobiological literature reviewed by Miller and Nair (2006) also indicates the existence of a great variety of indigenous agroforestry practices in Amazonia, ranging from deliberate planting of trees in homegardens and fields to the management of volunteer seedlings of both cultivated and wild species. These practices result in various configurations of agroforestry systems, such as homegardens, tree/crop combinations in fields, orchards of mixed fruit trees, and enriched fallows.

7.8 Research on Homegarden Systems

Despite being one of the oldest land-use systems in the tropics, research on homegardens is of relatively recent origin. The first available report dates back to the 1940s when Terra (1953, 1958) initiated investigations on mixed-garden horticulture in Java, Indonesia. Following that, Ruthenberg (1980) evaluated tropical mixed-species cropping systems in the 1970s and similar work was pursued at many institutions around the tropics; for example, The Institute of Ecology, Bandung, Indonesia (Soemarwoto 1987); the Central Plantation Crops Research Institute, Kasaragod, Kerala, India (Nair 1979); and elsewhere (e.g., Michon et al. 1983). The global inventory of agroforestry systems by ICRAF (International Centre for Research in Agroforestry) gave a further fillip to such efforts (Nair 1987), and several descriptions and syntheses of traditional homegarden systems followed (Nair 1989). Kumar and Nair (2004) summarized the patterns and trends in homegarden research during the previous 25 years and concluded that quantitative data on the biogeochemical and physiological processes in tropical homegardens are severely inadequate. Although tropical homegardens are a hot topic of discussion in most agroforestry conferences especially those covering humid tropical lowlands, focused research on the topic has, unfortunately, not gathered momentum possibly due to lack of institutional and policy support. Some notable publications on the topic include the proceedings of two international workshops: Landauer and Brazil (1990) based on the 1984 workshop in Bandung, Indonesia; and Watson and Eyzaguirre (2002) based on a 2001 workshop in Witzenhausen, Germany. Yet another collection of papers on the focal theme of this chapter is by Kumar and Nair (2006), based mostly on the presentations in a technical session on the topic at the First World Congress on Agroforestry, Orlando, Florida, 2004.

Historically, homegarden research mostly dealt with system descriptions and inventories. Agroforestry literature is replete with references to such accounts. Structural complexity and multifunctionality are intrinsic features of tropical homegardens, which received some attention. Other focal themes include food and nutritional security of the gardeners and other ecosystems services provided by the homegardens. Besides recording the local practices and species inventory, studies over the past 3 to 4 decades also highlighted the need for conservation of biocultural diversity (i.e., diversity exhibited by coupled or interacting natural systems and human cultures) and highlighted the socio-cultural dimensions of agrobiodiversity conservation, and the conventional uses of various plants.

7.9 Concluding Remarks

Homegardens have been globally recognized as harbingers of agrobiodiversity and providers of ecosystem services. They have also been acclaimed to mimic the structural and functional attributes of natural ecosystems, but that has been mentioned as a probable reason to “frustrate the development community that seeks out replicable models of development” (Nair and Kumar 2006). Furthermore, in the era of increasing emphasis on the market economy and yield maximization, the homegardens are not only being “ignored and left behind” but are also being transformed from their traditional subsistence outlook to market-oriented production enterprises. Such a drastic transformation will, unfortunately, lead to irreparable loss of genetic resources, biodiversity, traditional knowledge, and all such values of the homegardens that cannot be simply described by a price tag. All is not doom and gloom, however. There is a very welcome development that the message of homegardens seems to be getting recognized and appreciated in some industrialized countries and mega-urban centers of the world. Interest in sustainable land-use and organic farming is increasing rapidly in such industrialized societies. Urban food gardens are getting popularized under various labels in several megacities around the world as an approach to reconnect urban societies to nature. Perhaps the message and lessons that can be learned from the traditional homegardens hold their rightly deserving bright future.

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8 Shaded Perennial Agroforestry Systems

Contents

Abstract

The shaded perennial systems, also called plantation-crop combinations, include managed multistrata tree-crop associations predominantly in the tropics, in which the main crops are perennials that are harvested periodically like arable crops. These tree crops are economically and socially very important to the countries where they are cultivated because of the large number of people involved in the cultivation and processing of the products. The major tropical tree crops

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in agroforestry systems (AFS) include coconut (*Cocos nucifera*), coffee (*Coffea* spp.), and cacao (*Theobroma cacao*); oil palm (*Elaeis guineensis*), and rubber (*Hevea brasiliensis*) are also components of AFS to a limited scale. There are also several other types of shaded perennial systems that are less widely distributed, including black pepper (*Piper nigrum*) vines trailed onto the trunks of trees, and palms such as *Bactris gasipaes* (peach palm) and *Euterpe oleracea* (açaí or assai). The harvested products of almost all these tree crops need to be processed immediately after harvesting under exacting conditions to get the high-value end-products. Contrary to the popular image of largescale plantations associated with these crops, sizeable areas of most of them, particularly coconut, coffee, and several of the localized tree crops are cultivated in mixed (agroforestry) stands with other species on smallholder farms. Research on the high-value tree crops such as coffee, cacao, rubber, and oil palm has traditionally been well-organized but focused on maximizing the productivity of the harvested product of the crop raised in monocultural stands. Research on integrated smallholder crop combinations involving coconut palm, shaded coffee, and cacao has also progressed substantially since the late 1900s. Agroforestry systems involving these tree crops are receiving heightened attention nowadays in the context of the ecosystem services they provide and their potential role in climate change mitigation and biodiversity conservation.

8.1 Introduction

In most agroforestry systems, the crop components that are harvested regularly provide products of immediate value to the landowner, and trees are perceived as playing a supporting role in enhancing and sustaining the productivity of these crops. In some agroforestry systems (AFS), however, the trees themselves are the main "crops" and the other species – that could be annuals or woody or non-woody perennials – are grown beneath or between the "main" tree crops such that the main tree crops either provide shade to or receive shade from the companion species in the system. Different scenarios of such interesting plant associations are abundant in nature, but some of them have become prominent land-use systems because of the economic and commercial importance of the species involved. Three noteworthy categories of such prominent combinations involving shade-providing (overstory) and shade-receiving (understory) species are: 1. shade trees planted as part of growing a commercial crop such as coffee (*Coffea* sp.); 2. a commercial crop (e.g., cacao: *Theobroma cacao*) grown as an understory in an existing stand of commercial tree crop such as the coconut palm (*Cocos nucifera*); and 3. a shade-loving commercial crop (e.g., cardamom: *Elettaria cardamom*) grown under shade in a natural forest. Other types of shaded perennial systems that are less widely distributed than the above three categories are also common; trailing black pepper (*Piper nigrum*) vines onto the trunks of standing trees or on to specially planted live stakes is just one of them. The term shaded perennial system, also called plantation-crop combinations, is used to refer to all such multistrata systems that represent managed, vertically stratified plant associations involving shade-tolerant/adapted crops, aptly described as an "ecological marvel" (Nair 2017). The focus of this chapter is on such systems, in which the main crops are trees or other types of perennials that are harvested frequently like crops and grown mostly in commercial plantations but also in combination with other species in smallholder integrated farming systems. Several of the tree crops considered in this section are also grown in homegardens as described in Chapter 7.

8.2 Tropical Tree Crops: An Overview

8.2.1 Abundance and Distribution of Species

Tropical tree crops constitute an important component of land use in developing countries (FAO: http://faostat.fao.org). Because of the comparatively high commercial value of the final commodities and the large number of people involved in the cultivation and processing of these crops, they are very important, economically and socially, to the countries where they are cultivated. The major species of tropical tree crops in AFS include coconut (*Cocos nucifera*), coffee (*Coffea* spp. – *C. arabica* and *C.canephora* syn. *robusta*), cacao (*Theobroma cacao*), oil palm (*Elaeis guineensis*), and rubber (*Hevea brasiliensis*); the first three (coconut, coffee, and cacao) being more prominent than oil palm and rubber, in AFS. [Note: in this book, **cacao** is used for the plant and its parts – thus, cacao leaf, cacao stem, etc. – and **cocoa** for its commercial product: cocoa beans, cocoa powder, etc.],

The tropical tree crops are cultivated throughout the tropics, subject to ecological (climate and soil) conditions. The area under cultivation and production of all these crops has increased, some of them substantially, during the past 50 years (FAO statistics: http://faostat.fao.org). All these species except coffee are adapted to tropical humid lowlands with annual rainfall above 1000 mm per year (udic, isohyperthermic regimes = mean annual soil temperatures of about 22 °C and a difference between mean summer and mean winter soil temperatures of less than 5 °C at 50 cm below the surface; Köppen: Af, Am); coffee is adapted to humid tropical highlands at mid-elevations of up to 1300 m above sea level (udic isothermic = mean annual soil temperatures of 15–22 °C; Köppen Am, Aw).

In addition to the above species, several tree crops with similar general characteristics are cultivated throughout the tropics; but they are not as high-ranking as the "major" crops listed above in terms of the area under cultivation and total contributions to the respective national exchequers. Important among this category is cashew (*Anacardium occidentale*) adapted to a wide range of soil and climatic conditions, especially low rainfall and poorer soils. Tree spices such as cinnamon (*Cinnamomum verum*, syn. *C. zeylanicum*), clove (*Syzygium aromaticm*), nutmeg (*Myristica fragrans*), and allspice (*Pimenta dioica)* are also cultivated in AFS (Chapter 13).

The third category of tropical tree crops relevant to this chapter includes several "localized" species that are cultivated only in some specific regions; they are not cultivated – not even known – in areas outside their restricted areas of distribution and cultivation. While some of them have been domesticated and cultivated for long (e.g., arecanut, *Areca catechu*, in South and Southeast Asia), others have been domesticated and cultivated only recently (e.g., *Bactris gasipaes*, known as the peach palm in English, pejibaye palm in Spanish, and pupunha in Portuguese, grown in the Amazon basin and parts of Central America). Interestingly, although locations with similar ecological characteristics as those where such localized species are cultivated can be found in other places too, their distribution and cultivation remain localized.

It is difficult to estimate the area under tropical tree crops accurately because of the lack of standardized procedures for estimating areas as these species grow both naturally in scattered stands at varying densities and are planted and nurtured as a crop either alone or in combination with various other species. This situation raises doubts about the accuracy of their repeatedly used area-statistics (see, for example, Section 8.4 for the situation regarding the coconut palm). Equally unsatisfactory is the situation about their production statistics because a major share of the production of some of them (e.g., coconut) is consumed locally in the households without the products entering any form of marketing channels. Nevertheless, statistics on area and production have traditionally been compiled by local, regional, national, and international agencies, the most widely cited and supposedly authentic are the FAO statistics (http://faostat.fao.org). Considering the areas under the three categories of tropical tree crops described above (major as well as the "less" popular pantropical crops and the localized tree crops), it can be surmised that altogether these crops occupy about 10% of the total area under crop production in the tropics.

Tropical fruit trees such as *Citrus* spp., mango (*Mangifera indica*), and avocado (*Persea americana*) that constitute an important category of tropical tree crops are not included in this chapter. They are grown in commercial orchards as well as homegardens and other smallholder AFS and their mature fruits are ready for consumption without processing; but when grown in the latter category (homegardens and smallholder AFS), they are exclusively for household consumption and do not enter international trade and commerce. Extensive tree-intercropping systems such as the parkland system of West Africa based on the faidherbia tree (*Faidherbia* – syn. *Acacia* – *albida*) and the shea butter tree (*Vitellaria paradoxa*) that are seldom planted as plantations are also excluded from this chapter but discussed separately (Chapters 9, 13).

8.2.2 The Scale of Operations: Commercial Plantations and Smallholder Systems

An important feature of these tree crops is that the harvested products of both widely cultivated and localized species need to be processed immediately after harvesting under exacting conditions to get the high-value end-products that are graded and valued depending on their international quality standards and requirements. Driven by the lure of economic gains from these high-value crops, the cultivation of these crops (although only to a comparatively lesser extent for coconut) was promoted with scientific backing and developed as commercial, monocultural enterprises during the colonial times in Asia and Africa. Thus, large estates of single-species fields called plantations extending in area from 15 or 20 to hundreds – even thousands – of hectares are common, and these crops are usually perceived as being cultivated in such large plantations. The plantations have their facilities for processing the harvested products into commercial saleable commodities, and both production and processing are under the management of specialized teams. It needs to be noted here that "plantation" is a rather vague term that is also used to refer to large estates of monocultural stands of not only trees, but several crops such as pineapple (*Ananas comosus*), cotton (*Gossypium* spp.), sisal (*Agave sisalana*), and even corn (maize: *Zea mays*). The use of the term may not be prudent in some contexts because of likely implicit reference to the exploitation of slave labor for plantation agriculture in America in the past; but this stigma does not seem to exist outside the USA; for example, a major government institution in India, dealing with tree crops like coconut, cashew, and tree spices is called Central Plantation Crops Research Institute (http://www.cpcri.gov.in/).

Contrary to the popular image of largescale plantations associated with these crops, sizeable areas of most of them, particularly coconut, coffee, and several of the "localized" tree crops are cultivated in mixed (agroforestry) stands in association with other species on smallholder farms. Multiple photographs of several such tropical tree crops grown in smallholder agroforestry combinations in different geographical regions are presented as Figures starting with numbers 8.1, 8.2, 8.3 (coconut), 8.4, 8.5, 8.6, 8.7, 8.8 (coffee), 8.9, 8.10 (cacao), 8.11, 8.12 (rubber), 8.13, 8.14 (oil palm), and 8.15, 8.16, 8.17, 8.18 (other palms and miscellaneous species). When grown in AFS, these tree species can be either providers or receivers of shade. For example, the growth habits and species characteristics of single-stemmed tall palms such as coconut allow the cultivation of relatively shade-tolerant crops between or under them during their different growth stages (see Section 8.4). Rubber (Figures 8.11 and 8.12) and oil palm (Figures 8.13 and 8.14) are also used in AFS as shade-providers, although only to a comparatively limited scale. On the other hand, coffee (Figures 8.4, 8.5, 8.6, 8.7, and 8.8) and cacao (Figures 8.9 and 8.10), that are adapted to shade are widely cultivated as understory species along with taller trees that are known collectively as shade trees.

Figure 8.1 Banana (*Musa* sp.) as an intercrop under coconut palms. (Photo: ICRAF/World Agroforestry)

Figure 8.2 Pineapple (*Ananas comosus*) and papaya (*Carica papaya*) as intercrops under coconut palms. (Photo: ICRAF/World Agroforestry)

Figure 8.3 Young (about one-year-old) cacao (*Theobroma cacao*) under coconuts. (Photo: ICRAF/World Agroforestry)

Figure 8.4 Arabica coffee (*Coffea arabica*) under *Erythrina poeppigiana*. (Photo: Olivier Roupsard c/o Eduardo Somarriba, CATIE, Costa Rica)

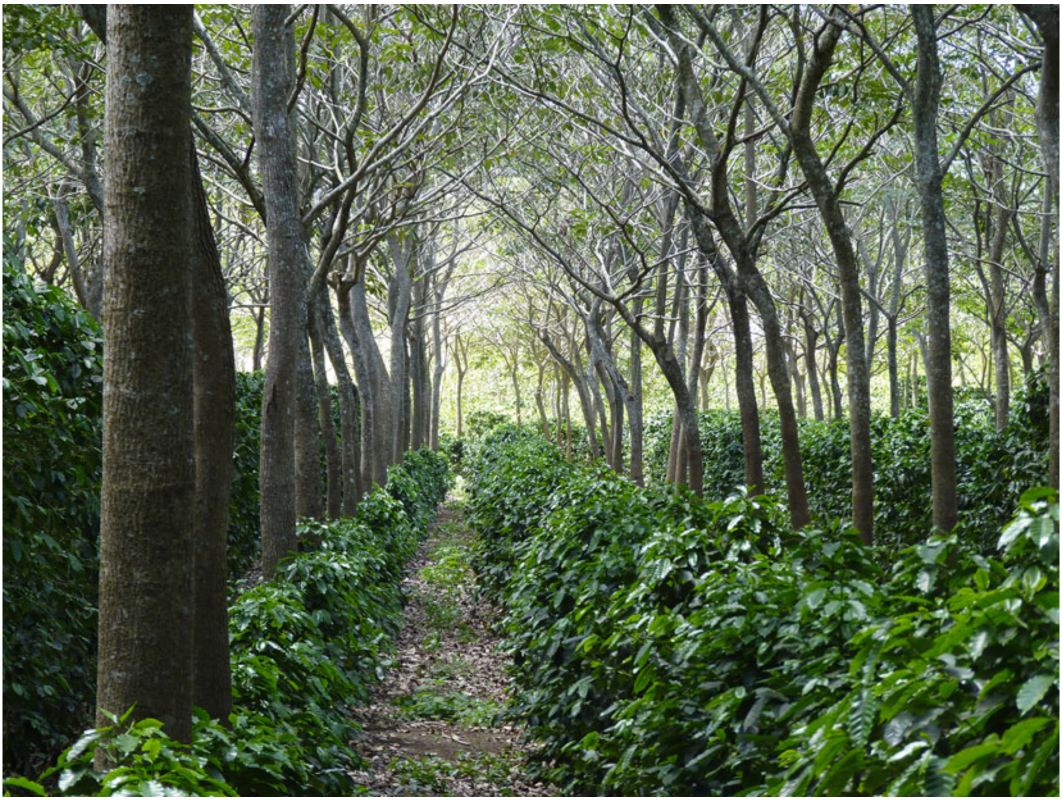

Figure 8.5 Arabica coffee (*Coffea arabica*) under timber trees. (Photo: ICRAF/World Agroforestry)

Figure 8.6 Coffee under the timber tree, *Cordia alliodora*, CATIE, Costa Rica. (Photo: PKR Nair 1982)

Figure 8.7 Coffee under *Grevillea robusta*, Hawaii. (Photo: Craig Elevitch)

Figure 8.8 Coffee with *Macadamia integrifolia,* Hawaii. (Photo: Craig Elevitch)

Figure 8.9 Cacao in a multistory combination, Cameroon. (Photo: E Torquebiau)

Figure 8.10 Cacao under shade trees, Karnataka, India. (Photo: ICRAF/ World Agroforestry))

Figure 8.11 Young (six-year-old) rubber trees (*Hevea brasiliensis*) + Black Pepper (*Piper nigrum*); Manaus, Brazil. (Photo: PKR Nair 1979)

Figure 8.12 Rubber (*Hevea brasiliensis*) + cacao, Bahia, Brazil. (Photo: Robert Miller)

Figure 8.13 Oil Palm (*Elaeis guineensis*) + cacao, Amazonia, Brazil. (Photo: Steel Silva Vasconselas, EMBRAPA, Brazil)

Figure 8.14 Oil palm, Açaí (*Euterpe oleracea*), cacao, and timber species; Belém, Brazil. (Photo: Steel Silva Vasconselas, EMBRAPA, Brazil)

Figure 8.15 Large cardamom (*Amomum subulatum*) under *Alnus nepalensis*, Sikkim, India. (Photo: PKR Nair 1985)

These tropical tree crops have relatively long lifespans ranging from about 30 years for coffee and cacao to nearly 100 for coconut and oil palm. Once the trees attain harvestable age, ranging from around 4 to 10 years after establishment depending on the species, they are harvested frequently like "crops" either seasonally one or two times a year (e.g., coffee and cacao), or multiple times a year (e.g., coconut), or even multiple times a week (e.g., rubber). These plants have low harvest index values [ratio of total aboveground biological productivity (biomass) to economic productivity (mass of harvested product removed from the system)]; in ecological terms, this means very low rates of removal (export) of nutrients from the system leading to efficient nutrient cycling within the system (see Chapter 16: Nutrient Cycling).

8.2.3 Research and Development Efforts

Research efforts on tropical plantation crops have essentially been commodity-oriented. Thanks to their economic importance, all the five major tropical tree crops (cacao, coffee, coconut, oil palm, rubber) have received substantial research attention especially during the 20th century, but to varying extents depending on the "economic might" of each, with rubber and coffee receiving the most, coconut the least, and cacao and oil palm in

Figure 8.16 Agroforestry with various specialty crops: vanilla (*Vanilla planifolia*) under the shade of clove trees (*Syzygium aromaticum*), Bahia, Brazil. (Photo: PKR Nair 1984)

between these extremes. Research and development of the crops had traditionally been organized as public, private, and joint operations in most countries depending on the local socio-political conditions and economic importance of the crops concerned. Thus, crop- and country-specific research institutions for rubber, coconut, coffee, and oil palm are found in almost all major producing countries, and they have helped enormously in the development of these commodities. For example, the contributions of the Rubber Research Institute of Malaysia, RRIM, established in 1925 (http://www.lgm.gov.my/general/rrim70yrs.aspx), to rubber cultivation and industry not only in Malaysia but the entire South- and Southeast Asia are substantial. The Central Plantation Crops Research Institute in India (referred to earlier in this section) has celebrated its 100th anniversary in 2016 (Nampoothiri et al. 2019). Regional and international research coordination is also promoted by multinational efforts for specific commodities. A notable institution of that category is CATIE: *Centro Agronómico Tropical de Investigación y Enseñanza* (Tropical Agricultural Research and Education Centre) in Costa Rica, established in 1972, a major center for research on coffee- and cacao-based AFS.

Commercial yields of some of these tree crops have increased considerably during the 1900s, whereas, for others, yields have been remarkably stagnant. A notable example of the former group is the rubber tree, referred to as Pará rubber tree signifying its native habitat of Pará state, Brazil. The average commercial yield of rubber has increased over 15-fold since its domestication in the 19th century. Students of agriculture and crop introduction cannot miss, and may get inspiration from, the legendary efforts of Sir Henry Wickham, the British explorer turned bio-pirate, who was responsible for bringing seeds of the rubber tree from its native Brazil to Kew Botanical Gardens in England in 1876. From there, the seeds were sent to Singapore Botanical Gardens and then introduced to Malaysia (today's

Figure 8.17 Agroforestry with various specialty crops: vanilla (*Vanilla planifolia*) under shade trees in Madagaskar (see also Figure 13.A.II.2, Appendix II, Chapter 13). (Photo: Dominik Schwab and Annemarie Wurz, Goettingen, Germany)

Singapore and Malaysia were British colonies at that time). The spread of the crop, especially its iconic RRIM clones, in Malaysia and subsequently in other countries of the region, and the contributions the crop has made to the economic development of the countries concerned are etched in golden letters.

The major crop in the category of tropical tree crops, the average yields of which have not increased substantially over the years is the coconut palm, although it has been cultivated since very early times and the economic values of its many products are well known. Both the area under the crop and its total production increased by about 2.5 times during the 50 years from 1961 to 2011 (Nayar 2019, based on FAOSTAT 2014), which means the average production per hectare has been almost stagnant. This contrasting situation between rubber and coconut represents a reflection of many factors, including how research is organized for these crops.

The land-use patterns of the tropical tree crops have not changed much with time: while the cultivation of rubber, coffee, cacao, and oil palm is organized as commercial enterprises and supported by considerable research attention from private sources and specialized commodity institutions, coconut, branded as a "lazy man's crop," is mostly grown in smallholder, subsistence farms. The commercial plantations have maintained their traditional characteristics of monocultural production of an export crop and extensive use of technological inputs and processing techniques. The plantation owners typically have seldom been concerned with annual crops except in the case of intercropping

Figure 8.18 Agroforestry with miscellaneous species: Areca palm, cacao, black pepper, in Karnataka, India. (Photo: Craig Elevitch)

Figure 8.19 AF with miscellaneous species 5: Tea (*Camellia sinensis*) bushes under the sparse canopy of *Grevillea robusta* trees with black pepper vines trailed on to tree trunks, Karnataka, India. (Photo: PKR Nair 2017)

during the early stages of plantation establishment. With the realization of the importance and necessity for intensification of land use due to rapidly increasing populations, planners and policymakers in tropical developing countries are gradually turning their attention to integrated production systems involving tree crops, annual crops, livestock production, and forestry. But all research and development efforts on these crops have been focused on maximizing the production of specific commodities, and all commodity-specific research institutions for these crops have been set up along specific disciplinary departments – often with traditional "turf" regulations – such as crop improvement and breeding, agronomy and soils, plant protection (entomology, pathology, etc.), post-harvest technology, and so on, with little or no attention being paid to integrated production systems. Thus, much of the voluminous results that are available on these crops are of only limited relevance to integrated systems.

With this backdrop, the developments in AFS involving the major tropical tree crops will be discussed in the following sections. It is not at all intended to review even superficially the voluminous, commodity-specific research on some of the crops that started decades ago and have been pursued in different institutions around the world. Indeed, such an effort will be redundant and unnecessary for the discussion, because, as noted, almost all such research and reports are focused on monocultural production systems of individual crops. Here, the discussion will be limited to AFS based on two types of tropical tree (plantation) crops. One is represented by coconut as "shade-providing" where the tree crop, which is not shade-tolerant, provides shade to companion species; the other is represented by coffee and cacao as "shade-receiving" where the main species is shade-tolerant and it receives shade from other species (shade trees) that are grown specifically for providing shade to the understory species.

8.3 Integrated, Smallholder Land-Use Systems with Shaded Perennial (Plantation) Crops

The scope for integrated practices involving plant associations is limited in modern commercial plantations of tree crops like rubber and oil palm except perhaps during the early phases of plantation establishment. Given that the commercial production of these crops has been developed with the single-commodity objective, multi-use resource development in large-scale plantations is considered impractical; arguably, diversified production strategies impede the modernization and efficiency of plantation management technologies. Thus, there is no compelling rationale for diversified production in such plantation areas; nor has the technology for such possibilities been developed to make them economically attractive. On the other hand, under smallholder farming conditions, the two major resources – land and capital – are limiting, and the farmer's objective is not the maximization of any single commodity.

Smallholder farmer (often wrongly referred to as "small farmer") is a loosely defined and intuitively understood, yet widely used term (see Chapter 23). In socioeconomic terms, a small farm is commonly defined as "farms where the resources such as land and labor available to the farmer (owner) severely limit opportunities for improvement," but this definition has some clear limitations. A working definition could be "a farm that is more of a home than a business enterprise," so that farm-management decisions are made based on household needs rather than business interests (Hildebrand 1988; Chambers et al. 1995). The size of a "small farm" varies widely in different places: while a small farm in Bangladesh is a fraction of a hectare, it is 50–100 ha in northern Brazil. In ecologically high-potential areas, the small farms are comparatively smaller in size than those of low-potential areas. In many such cases, especially in densely populated areas, farmers usually integrate annual crop- and animal production with perennial crops primarily to meet their household food requirements. Some reports suggest that small farms produce up to 70% of the total food produced in the tropics (FAO 2015). Although the validity of such high numbers has been questioned (see Chapter 23), the important role of smallholder farming systems in meeting the world's food and nutrition is universally accepted (van Vliet et al. 2015). It is for these innumerable smallholder farms that perennial-crop associations and integrated land-use practices are becoming increasingly important. Some characteristics, both socioeconomic and biological, are common to all these smallholders (Hildebrand and Poey 1985; Chambers et al. 1995). The resources available to the farmer severely limit opportunities for improvement. Farm size is often small, and family labor is usually underutilized on a year-round basis but is inadequate during periods of peak requirements. Owner-operated smallholder systems use "free" family labor or low-cost hired labor, usually with more working days per worker, as well as more hours per working day, as compared to commercial, large-scale plantations. Modern production technologies that are developed for and well-adapted to commercial plantations are of little value to such small farms.

Several reports are available on the practice of integrated smallholder systems with tropical tree crops in different places (Ruthenberg 1980; Nair 1983, 1989; Watson 1983). Most of the cacao production in Ghana and Nigeria comes from smallholdings of various sizes less than 5 ha, where cacao is grown in association with food crops such as maize, cassava, banana, cucumber, and sweet potato, especially during the first four years after planting cacao. In Trinidad, cacao is mainly a forest species, grown under shade trees, with no fertilizer or pesticide application. Many smallholder rubber plantations in southeast Asia and Nigeria are based on integrating rubber with a variety of crops, including soybean, maize, banana, groundnut (peanut, *Arachis hypogaea*), fruit trees, black pepper (*Piper nigrum*), and coconuts. In Malaysia, poultry raising in rubber stands is also a common, remunerative practice (Ismail 1986). Notable examples of smallholder systems in which coffee is integrated with other crops and/or livestock include the banana and coffee, and maize and coffee smallholdings of East Africa, especially in the highlands of Ethiopia, Kenya, and other countries of the region. Most of the coconut production in India, the Philippines, Sri Lanka, and the Pacific Islands comes from smallholdings, in which the coconut palm is integrated with several annual and perennial crops. In Sri Lanka and the Pacific Islands, grazing under coconut is also common. In India, Tanzania, Mozambique, and Senegal, smallholders often grow cashew trees with other crops; grazing under cashew is also common, particularly on smallholdings in East African coastal areas.

Perennial crops encourage the farmer to take up a more sedentary lifestyle than do annual crops and may contribute to increased motivation for investment in permanent housing and agricultural improvements (e.g., irrigation systems). These crops are often considered the basis of a family's wealth and security. Additionally, the relative constancy of yield and year-round production of some of these crops (e.g., coconut, rubber), have made them reasonable insurance against the risk of total crop failure that is common for rainfed, seasonal crops in the tropics. Cropping systems consisting of perennial plant associations also offer improved chances for conserving the soil and soil fertility due to the presence of a permanent plant cover and the addition of leaf litter to the soil, and they lend themselves, in some cases, to reduced tillage operations. Disincentives of perennial-crop cultivation include the relatively long time-lag between planting and profitable production, long-term commitment of the land to a crop for several years or even decades, the high initial investment in capital and labor costs, processing requirements of some crops, and the special management skills and diverse maintenance operations that are usually needed.

8.4 Coconut-Based Smallholder Systems: A Notable Example of Integrated Agroforestry

8.4.1 Common Land-Use Features of Coconut-Based Ecosystems

The coconut palm (*Cocos nucifera* L., family Arecaceae), the most widely cultivated palm and a major tropical tree-crop, is one of the earliest among domesticated plants. It has been described with various adulations and accolades, indicating the usefulness of its various parts and products. The palm has been and still is an intimate part of the bio-cultural legacy and economic wellbeing of the populations of its principal growing regions. As Purseglove (1972) states, coconut's uses are legion; every part of the palm is useful to man in one way or another.

The uncertainties in presenting the area and production statistics of tropical tree crops noted earlier (Section 8.2) are most applicable to coconut. The palm is reportedly cultivated in 94 countries in about 12 million ha (Nampoothiri et al. 2019), mostly on islands, peninsulas, and along coasts, and it is the most ubiquitous plant species in its growing regions. More than 90 percent of the crop is in Asia and Oceania; the major producing countries are the Philippines, Indonesia, India, Sri Lanka, Malaysia, and the Pacific islands. Although often portrayed as a largescale plantation crop, most of the world's production of coconuts is from numerous smallholdings of less than 2 ha (Figure 8.19).

8.4.2 Growth Habits of the Coconut Palm Concerning Multispecies Systems

Being a single-stemmed perennial with no cambium, the main stem (trunk) of the palm does not increase in girth with age. Indeed, palms in general – coconut in particular – are distinctive organisms that can make tall and long-lived trees entirely by primary developmental processes, i.e., all the tissues are the direct result of continuously active root and shoot apical meristems, which explains why palms of any age can be successfully transplanted to new locations. The palm's apical crown at the growing tip of the trunk contains 30–40 long leaves at any time and a crown with a diameter of about 7 m throughout its adult life from about 10 to 70 years. In a uniform (planted) stand of palms, this characteristic growth habit allows considerable light penetration to the plantation floor as the palm grows taller with age (Figure 8.22). In natural stands, this allows understory growth of younger coconut palms or a variety of shade-tolerant other species. Thus, smallholder farms of coconut that predominate the coconut areas consist mostly of palms in association with a variety of other species of all types: herbs, shrubs, vines, and trees (Figures 8.1, 8.2 and 8.3). Exceptions to this general rule of smallholder farms are found in commercial holdings, as in large "coconut estates" that were developed in the Pacific islands by the European settlers during the 20th century (Bonnemaison 1996). In such situations, stands of palms of uniform age planted at 7.5 m square configuration, giving about 180 palms per ha, are the norm.

The amenability of coconut stands for intercropping depends primarily on the growth stages of the palm. Based on the amount of light transmitted through coconut canopy during the palm's growth stages, Nelliat et al. (1974) divided the life span of the palm into three distinct phases from the perspective of intercropping in a sole stand of palms.

1) Interplanting until full development of palm canopy (up to 8 years after planting) when a major portion of the incident light (solar energy) is not intercepted by the coconut crown, owing to its relatively small crown size. The availability of light to understory (plantation floor) decreases progressively with the age of palms during this pre-bearing period (Figure 8.23). This phase of the coconut life cycle is suitable for growing relatively short-duration crops such as cereals, grain legumes, vegetables, spice crops, fruit crops like banana, and pineapple (*Ananas comosus*).
2) Young palms between 8 and 25 years of age, characterized by maximum ground coverage and low trunk-height that limits light penetration to lower story and thus limits opportunities for understory cropping. At this

stage, however, shade-tolerant perennial crops such as black pepper, cacao, and fruit trees could be planted. These crops that also have a slow growth rate during their establishment phase get established gradually as the coconut trunk elongates with age.

3) Mature palms (more than 25 years) are characterized by increasing trunk height and reduction in crown size because of the drooping of long leaves, resulting in increased light transmission to the understory with the increase in palm's age. This is the phase that is ideal for raising annual as well as perennial crops with coconuts in multistory cropping configurations.

8.4.3 Intercropping Under Coconuts

Considering the demographic and socioeconomic characteristics of smallholder areas where coconuts are grown and the growth habit of coconut palm, it is only logical and natural that integrated land-use practice involving several species are a common feature in such areas. As described above, except during the period from about the eighth to the twenty-fifth year of the palm's growth, the solar radiation reaching the understory may be adequate to permit the growth of other compatible species. The transmission of light to the lower profiles in palm stands of varying age groups, and the general pattern of coverage by a coconut canopy are shown in Figure 8.22). Additionally, the rooting pattern of the palm in a managed plantation is such that most of the roots are found near the bole (Nelliat et al. 1974), and thus overlapping of the root systems of the palm and the intercrop species is minimal (Figure 8.23). Indeed, the localization of the root systems of different species in a multispecies combination, with minimal overlapping of root systems of the component species, is an important aspect of the niche complementarity among species in a desirable multistoried crop combination of coconut, cacao, and black pepper as shown in Figure 8.24. Based on these considerations, Nair (1979) suggested a plant association pattern for coconuts of different age groups. Such intercropping practices under or between coconuts with a variety of other useful species are common in most coconut-growing regions of the world. The multi-species, multi-strata systems with coconut managed as smallholder family-farm enterprises, acclaimed as "an agroecological marvel" (Nair 2017), are now common on the west coast of India (Figures 8.20, 8.21 and 8.23) and other places.

Numerous reports are available on intercropping with coconuts and the array of crops grown in different countries and regions. Thomas et al. (2019) compiled a good summary, mostly of reports from India. The species intercropped consist of food crops including roots and tubers, fruit trees, tree-plantation crops, medicinal plants, multipurpose trees that provide products such as food, fuel, fodder, timber, medicine, and such other necessities, and help meet the cash requirements of the growers (Kumar 2007). Just as there is no uniformity in palm spacing, planting pattern, or palm age in most of the smallholder coconut areas, there is no regularity or systematic pattern for intercropping. In many cases, several crops are grown together on the same piece of land in complex systems. Descriptors for these systems are similarly diverse. The choice of the intercrops and their cropping pattern depend on several factors such as demand or market for the product, climatic and soil characteristics, age and management level of the palms, and growth habits of the intercrop.

Numerous terms are used to describe the various practices of crop combinations with coconuts. In India, the term ***intercropping*** is used for the practice of growing annuals or other short-duration crops under perennial species, whereas ***mixed cropping*** denotes growing other perennials in the interspaces of perennial plantations. ***Multi-storied cropping*** is a term used to refer to multi-species combinations involving both annuals and perennials (Nelliat et al. 1974; Nair 1979), and ***mixed farming*** refers to combined crop and livestock production. Another term that is becoming common is the **coconut-based farming system, CBFS** (Thomas et al. 2019; see also Section 8.4.4). Interestingly, in the description of

Figure 8.20 Multistory agroforestry: Coconut palms form the top-level canopy, black pepper trailed onto its trunks and banana constitute the middle-level canopy, and pineapple (*Ananas comosus*) and cowpea (*Vigna unguiculata*) form the lower level canopy at CPCRI, Kasaragod, India. (Photo: PKR Nair)

Figure 8.21 Another multistory agroforestry combination with coconut palms, black pepper, bananas, clove trees, moringa, and pineapples, at CPCRI farm, Goa, India. (Photo: PKR Nair)

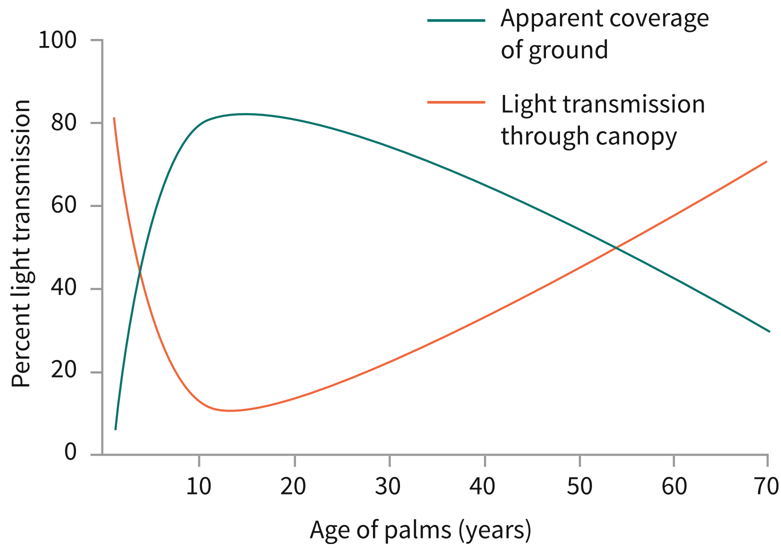

Figure 8.22 Light distribution in coconut stands of varying age groups. (Source: Adapted from Nair 1979)

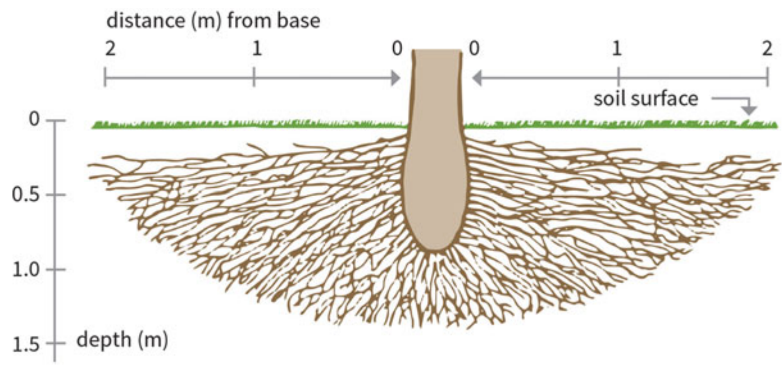

Figure 8.23 Rooting pattern (schematic) of a coconut palm. The roots are concentrated in an area about 2 m horizontally and 1.5 m vertically from the bole. (Source: Adapted from Nair 1979)

CBFS, the authors have included a category called "coconut-based agroforestry system" that includes only combinations of coconuts with just a few other trees, especially the nitrogen-fixing trees such as *Acacia mangium*, *A. auriculiformis, Casuarina equisetifolia, Gliricidia sepium,* and *Leucaena leucocephala* primarily for producing animal fodder or firewood. This is a narrow perception stemming from the past, obsolete way of categorizing plants as either agricultural species or forestry species. All plant associations with coconuts, irrespective of whether the associated species is or used to be called agricultural, horticultural, forestry, or by some such traditional terms, are coconut-based agroforestry systems (Nair 1983, 2014).

Although research on such crop combinations with coconuts has been carried out since the 1970s before agroforestry came of age, only a few results have been published, and most of them are from coconut-based systems in India (Nair 1979; Nelliat and Bhat 1979), Sri Lanka (Liyanage et al. 1984, 1989), and the Far East and the South Pacific (Plucknett 1979; Steel and Whiteman 1980). Most such reports describe local experiences of intercropping with details of species used, their management details including fertilizer application, intercrop yields, and

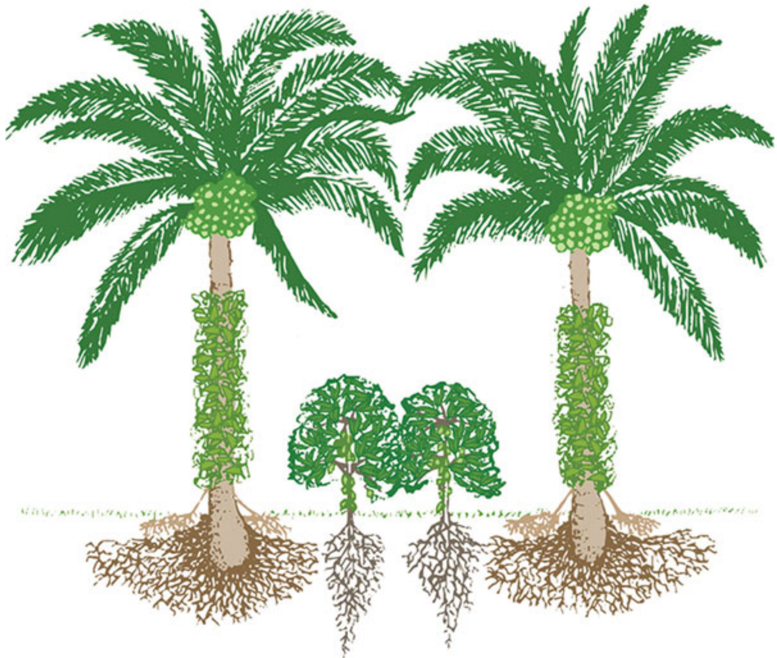

Figure 8.24 Rooting patterns (schematic) of the components of a multistory combination of coconut palm, cacao (*Theobroma cacao*) and black pepper (*Piper nigrum*). The localization of root systems of the different components with minimal overlapping is an important aspect of the complementarity among the species that contributes to the success of the overall system. (Source: Adapted from Nair 1979)

economic benefits calculated based on local market data. In some cases, the effect of intercropping on coconut yields are also reported, but long-term trends on such aspects have rarely been reported.

8.4.4 Special Forms of Integrated Production Systems with Coconuts

In addition to the multi-species, multi-strata tree-, shrub- and field-crop systems with coconuts, a special type of integrated coconut-based farming system is common in several southeast Asian countries involving farm animals such as cow, goat, poultry, duck and rabbit, and pig, and aquaculture (shrimp-, prawn-, and fish farming). These are well-maintained holdings in which the companion species grown with coconuts are carefully chosen; invariably, food crops that produce a reasonable yield under partial shade are a natural choice. Various tuber crops such as cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and different species of yams (especially *Dioscorea* spp.), as well as several kinds of vegetables, are common choices. Rhizomatous, shade-tolerant tropical annuals with proven medicinal values such as ginger (*Zingiber officinale*) and turmeric (*Curcuma longa*) are commonly grown as intercrops under coconuts in South- and Southeast Asia. Where the plant density of palms is lower and other conditions are favorable, crops that require more sunlight, such as cereals and grain legumes, are also grown, but usually, the intercropped cereals yield comparatively less than in their sole-cropped stands.

Other integrated, labor-intensive systems of livestock production with coconuts are also found in some places, especially in Southeast Asia and the Pacific Islands (Plucknett 1979). Cattle raising usually involves grazing on pastures composed of natural species; in some cases, special fodder plants are also cultivated. In natural stands, the most important plants for grazing are grasses and legumes although many other types of plants that can be grazed are also found. Some of the species that are commonly considered weeds in coconut gardens are also grazed; moreover, cover crops such as kudzu (*Pueraria phaseoloides*), centro (*Centrosema pubescens*), and calopo (*Calopogonium mucunoides*) can be found in natural pastures. The carrying capacity of unimproved natural pastures varies widely depending on factors such as the type of plants, climatic condition, age and stand density of the palms, degree of weed intensity, and so on. Surveying the available literature on the subject, Plucknett (1979) found that the carrying capacity on natural pastures varied from 1 to 2 hectares per head of cattle. Cattle raising on natural pastures under coconut is an extensive land-use system with little management input. On the other hand, improved pasture species and good pasture management techniques are common in some coconut-growing areas, especially in the Pacific islands. Management practices include different stocking rates, use of different grazing intensities, use of fertilizers, selection of pasture species or mixtures, weed control, and fencing, and the management system varies greatly depending upon climatic factors (particularly rainfall), soil type, and the farmer's skill. Mack (1991) and UNESCO (1979) who reviewed the constraints to farmers' adoption of grazing under coconuts reported that the farmers' reluctance to learn such additional techniques associated with animal husbandry and improved pasture management was a major one. The effects of grazing and improved pasture management techniques on coconut yields have also been studied, particularly at the Coconut Research Institute in Sri Lanka. The results indicated that, as with the case of intercropping (Section 8.4.5), the pasture will not diminish the yield of palms if both components of the system (coconuts and the pasture) are adequately fertilized and managed well (Santhirasegaram 1975).

8.4.5 Prospects of Land-Use Intensification with Coconuts

Perhaps the most important incentive for adopting intensive land-use systems with coconuts is the immediate economic benefit. Nevertheless, the desirability of intercropping from the perspective of the long-term productivity of coconut is also an important issue. Published reports and experimental evidence indicate that the palm's productivity level depends on the level of management. A major consideration is the extent of plant-to-plant interactions. Neighboring plants will often draw on the same pool of environmental resources at both above- and belowground levels. A compilation of the available reports indicates that intercropping in the interspaces under trees does not exert strong negative effects on the yield of coconut palms unless such trees grow taller and reduce light availability to coconut crown (Kumar 2007). Investigations at the CPCRI (Section 8.2.2) have shown that if both the main crop and the intercrop are adequately manured and managed, intercropping is not harmful to coconut production (Nair 1979; Thomas et al. 2019). On the other hand, if the additional crop becomes a "parasite" on the main crop, the yields of both components of the mixture will be adversely affected. Interaction between neighboring plants need not always be negative either. Plants may complement each other in sharing pools, thus achieving a more complete utilization of resources. The root distribution patterns of individual species in the plant associations are very important: Nair (1979, 1983) reported such a favorable rooting configuration in a multistoried crop combination of coconut, cacao, and pineapple as discussed earlier (Figure 8.24). Another manifestation of plant-to-plant interaction is the microclimate of the plant community: an example of biological complementarity has been noticed in a crop combination of coconut and cacao at CPCRI (Nair and Balakrishnan 1977). The yield of coconuts increased when they were grown in combination with cacao, compared to sole-stand coconut yields (Nair 1979). The performance of cacao as a sole crop is a moot point given that cacao is always grown under shade. The exploitation of such beneficial interactions could enhance the productivity of coconuts and other species in a combined system. The traditional emphasis on the effect of intercropping on the yield of the "main" crop, however, is baseless if the overall productivity and economic returns per farm or unit of land are taken as the criterion for comparison; but that involves an attitudinal difference in the outlook and perception that may be difficult for the norms of traditional farming communities.

The intensification of land use in existing coconut areas is not without problems and limitations, nor is it of universal applicability. The potential is confined to those areas where soil and other ecological conditions permit such practices. Environmental resource limitations may impose restrictions on the crops and cropping patterns. Lack of proper management of the crop combination could also result in undesirable effects and certain pest problems can be enhanced by growing two or more crops together. As regards the availability of area for intercropping, the shade cast by the palms – a consequence of their planting configurations – is the most decisive factor.

Institutional research support and incentive programs for coconuts are still directed heavily toward enhancing the productivity of coconuts in monocultural stands. Although low-intensity intercropping has a long tradition mainly among subsistence farmers, the practice has been looked down upon by researchers who have mostly been trained and encouraged to follow conventional, discipline-oriented research outlooks. During the past two decades (since 2000), however, many farmers, lured by the prospects of economic advantages, have adopted high-intensity multi-species cropping with coconuts on the west coast of India. This provides a clear case of the dichotomy between the objectives of conventional research and farmers' perceptions. The tides are changing, however; a much-needed paradigm shift is happening in research directions related to coconut ecosystem management. The benefits of climate change mitigation potential offered by multi-species combinations are another factor that strongly supports such a paradigm shift in research priorities (see Chapter 20).

8.5 Shaded Coffee and Cacao Systems

Coffee and cacao are two pantropical tree crops of enormous economic importance grown in agroforestry systems in the humid and sub-humid regions with elevations up to about 2,000 m above sea level. An estimated 145 million people depend on coffee and cacao for their livelihood, and billions savor their products. In addition to these two principal tree crops, some other "localized" shade-adapted tropical tree crops are grown in AFS; for example, Yerba maté (*Ilex paraguensis*) in Paraguay (Evans and Rombold 1984) and cupuaçu, pronounced cupuassu (*Theobroma grandiflorum*) in the Amazon basin, are usually grown under shade trees. Then, there are commercially important perennial vines such as black pepper (*Piper nigrum*) that are traditionally grown by trailing them onto trees or dead standards, the former in agroforestry systems and the latter in commercial plantations. Combinations of these species under a variety of overstory species are quite common. The ecological principles and socioeconomic objectives involved in crop combinations of all such crops are basically similar.

8.5.1 Shaded Coffee Systems

The coffee plant belonging to the family Rubiaceae is a short tropical woody species, originally described botanically as *Jasminum arabicanum* (by Antoine de Jussieu in 1713) and later classified as *Coffea arabica* (by Linnaeus in 1737). Its primary center of origin is the highlands of southwestern Ethiopia. The international coffee trade involves only two species of *Coffea* – *C. arabica* (Arabica coffee) and *C. canephora* (Robusta coffee). Between these two species, the native distribution of *C. canephora* (syn. *C. robusta*) is much wider extending from West to East Africa (Krishnan 2017). Coffee is cultivated in about 50 countries, the top 10 in 2015 being Brazil, Vietnam, Colombia, Indonesia, Ethiopia, and India, Honduras, Uganda, Guatemala, and Peru, in areas located between latitudes 22° N and 26° S. The optimal growing temperatures for Arabica coffee are 18 °C (night) and 22 °C (day), with tolerated extremes extending from 15 °C to 30 °C. Robusta coffee can tolerate slightly higher temperatures, with optimal temperatures between 22° and 28 °C. Most coffee-growing regions are typically rain-fed, with an annual rainfall of 1,400 to 2,000 mm for Arabica and 2,000 to 2,500 mm for Robusta. Rainfall below 800 mm for Arabica and 1,200 mm for robusta can result in poor productivity. The plant starts bearing in 3–4 years after planting and productivity declines after about 30 years. Plentiful descriptions of the coffee plant and its cultivation and management are available in print as well as on the Internet, and various aspects of production and trade statistics of coffee are available from ICO, International Coffee Organization, London (www.ico.org).

Coffee is adapted to shade and has traditionally been grown under the shade of other trees (shade trees). The need for shade for coffee (sun coffee vs. shade coffee) has been a debated issue since the beginning of the commercial cultivation of coffee. Since the mid-1970s, sun-tolerant coffee shrubs that are higher yielding and resistant to the coffee leaf rust fungus (*Hemileia vastatrix*) that causes the devastating fungal disease have been developed and are increasingly being cultivated as sun coffee (without shade trees). However, serious concerns about the (proven) negative impact of the production of sun coffee on the environment (use of chemicals, biodiversity decline, etc.), lower quality (taste) of coffee, and potential health hazards of both the drinkers of sun coffee and the farmers who handle the chemicals in the field have caused a trend in support of shade-grown coffee. Whatever be the trends in public opinion on this matter, a major share of coffee of international trade is – and, in all probability, will continue to be – produced under shade and most of it in smallholder agroforestry systems. Photographs of some coffee-agroforestry systems are included as Figures 8.4, 8.5 and 8.6.

8.5.2 Cacao Production Systems

Cacao (*Theobroma cacao*) is a small evergreen tree, 4–8 m tall, belonging to the family Malvaceae. Native to the tropical forests of the Americas and domesticated more than 3,000 years ago, cacao is cultivated over about 11 million ha worldwide in 50 countries, some in large commercial plantations, but mostly in small plots by millions of smallholders in the humid tropical belt between 10° N and 10° S of the equator. The natural habitat of the cacao tree is in the lower story of the evergreen rainforest, and climatic factors, particularly temperature and rainfall, are important in encouraging optimum growth. The plants respond well to relatively high temperatures, with a maximum annual average of 30°–32 °C and a minimum average of 18°–21 °C. Details about global production and trade statistics are available from the International Cocoa Organization (ICCO), Abidjan, Côte d'Ivoire (http://www.icco.org). The major producing countries (2017) are Côte d'Ivoire (Ivory Coast), Ghana, Indonesia, Nigeria, Cameroon, Brazil, and Ecuador (ICCO: 20 June 2019), with 60% of the world's chocolate being produced by smallholder farmers in Côte d'Ivoire, Ghana, and Indonesia. In 2016, the global chocolate market was valued at USD 99 billion. Three main cultivars are recognized: Forastero, Criollo, and Trinitario. The Forastero group accounts for about 80% of the commercial chocolate; Criollo, the most prized and rare and accounting for only 10% of chocolate, is less bitter and more aromatic than any other beans. The plant takes over five years to come into production, and a further 10 to 15 years to reach its full bearing potential. It is traditionally grown under shade (Figures 8.9 and 8.10) and shading is indispensable during its early years.

8.5.3 Shade Trees for Coffee and Cacao

Both crops being high-value global commodities, a considerable amount of research has been conducted on them and voluminous scientific and technical reports are available, ranging from the early books to modern Internet sources. As in the case of coconut and such other plantation crops discussed earlier in this chapter, most of the research and development efforts are commodity-oriented on the specific species (coffee, cacao, or others) in monocultural stands, not in integrated systems, although sizeable area and production of these crops are in integrated systems. An important component of such integrated systems is the shade tree. The information base on shade trees and their management is relatively better for coffee than for cacao. While there are relatively more uniformity and specificity on shade trees for coffee in different coffee-growing regions, cacao is grown under the shade of almost any plant that provides shade ranging from tall-growing bananas to large trees. De Sousa et al. (2019) included 100 species identified as shade trees used for coffee and cacao in Mesoamerica for their study on the potential impact of climate change on the likelihood of replacing coffee with cacao, indicating the wide spectrum of species used as shade trees. Similarly, Asare (2005) and various others have reported rather long lists of shade trees used in cacao cultivation in West Arica. Since coffee and cacao are often grown in the same locations in many regions, their shade trees are also common. A list of common species of shade trees for these crops is included in Table 8.1; species profiles of some of the prominent ones are included in Chapter 13, Annexure 13-I. Many of these are naturally regenerated while some of them are planted especially in plantations and homegardens. Scientific studies on the role and management of shade trees have been limited to a few species – more for coffee and less for cacao – and no effort seems to have been done on plant improvement (breeding, selection, etc.) of shade trees.

Several national institutions in the major producing countries, as well as regional and international organizations, have been involved in studies on coffee and cacao production and management. A prominent one among them in Central America is CATIE, Costa Rica (Section 8.2.3). Much of the research on these systems at CATIE since its establishment in the 1970s has concentrated on shade trees and nutrient-related issues. A long-term replicated experiment, established in 1977 and known as "La Montana," has produced a significant amount of data on such topics as organic matter, nutrient cycles, litterfall, and water infiltration (Fassbender et al. 1988; Imbach et al. 1989). The tree species used in this experiment are *Erythrina poeppigiana*, which is periodically cut back (Figure 8.4), and the valuable timber species, *Cordia alliodora*, the stand of which is periodically thinned (Figure 8.6). Comparing the two species, researchers at CATIE (Beer 1987, 1989; Fassbender et al. 1988; Beer et al. 1990) showed that *E. poeppigiana*, when pruned two or three times a year, with the prunings added to the soil, can return the same amount of nutrients to the litter layer of coffee plantations as the crop fertilized with inorganic fertilizers at the highest rates recommended for Costa Rica (270 kg N ha^{-1} yr^{-1}, 60 kg P ha^{-1} yr^{-1} and 150 kg K ha^{-1} yr^{-1}). The annual nutrient return in litterfall represents 90–100 percent of the nutrient store in the aboveground biomass of *E. poeppigiana*. In the case of *C. alliodora*, which is not pruned, nutrient storage in the tree stems, particularly of potassium, is potentially a limiting factor to both crop and tree productivity (Fassbander et al. 1988). This suggests that, in fertilized plantations of cacao and coffee, litter productivity of shade trees is an important factor, possibly even more important than nitrogen fixation. Summarizing 10 years of results of these experiments at CATIE, Fassbender et al. (1991) reported that the average cacao bean harvest during the ages of 6–10 reached 1036 and 1057 kg ha^{-1} yr^{-1} under shade of *C. alliodora* and *E. poeppigiana*, respectively. Several other research results and synthesis reports have also been produced in subsequent years; the best source for databases and information is CATIE (Somarriba et al. 2012). Major research results on coffee- and cacao AFS reported from institutions around the world and included in this book are soil productivity and carbon-and-nutrient-cycling (Chapters 16, 20) and biodiversity conservation and other ecosystem services (Chapter 21).

An area of current interest (since around 2010) is the relevance of coffee and cacao AFS in climate-change mitigation and adaptation (see Chapter 20), and the role of shade trees in mitigating the impacts of climate change. The study by de Sousa et al. (2019) referred to above suggests that replacing coffee with cocoa and integrating trees in combined agroforestry systems to ameliorate abiotic stress are among

Table 8.1 Common shade trees used for coffee and cacao agroforestry systems

Genus	species	Family	Remarks
Acacia	*mangium*	Leguminosae (Fabaceae	Timber
Albizia	*lebbeck, saman*		Timber
Anacardium	*excelsum, occidentale*	Anacardiaceae	
Anona	*cherimola, muricate, reticulata, squamosa*	Annonaceae	Fruit
Artocarpus	*altilis*	Moraceae	Fruit
Bactris	*gasipaes*	Arecaceae (Palmae)	Fruit
Areca	*catechu*		Fruit
Bursera	*simaruba*	Burseraceae	Timber
Carapa	*guianensis*	Meliaceae	Timber
Cecropia	*obtusifolia*	Urticaceae	Timber
Cedrela	*odorata*	Meliaceae	Timber
Ceiba	*pentandra*	Malvaceae	
Chrysophyllum	*oliviforme*	Sapotaceae	Timber
Citrus	*limon, reticulata, sinensis*	Rutaceae	Fruit
Cocos	*nucifera*	Arecaceae	
Cola	*nitida*		
Cordia	*alliodora*	Boraginaceae	Timber
Dacroydes	*edulis*		Fruit
Dalbergia	*glomerata*	Leguminosae (Fabaceae)	Timber
Enterolobium	*cyclocarpum*		Timber
Erythrina	*berteroana, poeppigiana*		N_2 fixing
Gliricidia	*sepium*		
Inga	*edulis, jinicuil, nobilis, spectabilis, vera*		
Jetropha	*curcas*		
Khaya	*ivorensis*		
Leucaena	*leucocephala*	Leguminosae	N_2 fixing
Mangifera	*indica*	Anacardiaceae	Fruit
Manilkara	*zapota*	Sapotaceae	Fruit
Milia	*excelsa*		
Pentaclethra	*macroloba*	Leguminosae	Timber
Persea	*americana*	Lauraceae	Fruit
Psidium	*guajava*	Myrtaceae	Fruit
Schizolobium	*parahyba*	Leguminosae	Timber
Simarouba	*glauca*	Simaroubaceae	Timber
Spondias	*dulcis, mombin, purpurea*	Anacardiaceae	Fruit
Swietenia	*macrophylla*	Meliaceae	Timber
Syzygium	*aromaticum, jambos, malaccense*	Myrtaceae	Timber
Tabebuia	*rosea*	Bignoniaceae	Timber
Terminalia	*amazonica, ivorensis, oblonga, superba*	Combretaceae	Timber

Source: Compiled from various sources

the proposed alternatives to overcome the challenges posed by climate change. The authors predict that cacao could potentially become an alternative in most of the vulnerable coffee areas and suggest that transforming agroforestry systems by changing tree species composition is the best approach in most of the coffee production areas in Mesoamerica, where the study was focused on.

8.6 Other Agroforestry Systems Involving Tropical Tree Crops

8.6.1 Tropical Palms

The palm family (Arecaceae; Palmae) comprising around 2440 species (Dransfield et al. 2008) constitutes one of the important families in rural areas of the tropics, especially the humid tropical zone (Johnson 2011), being next only to grasses (Poaceae = Graminae) and legumes (Fabaceae = Leguminosae) in their worldwide economic importance. Most palms have a modular growth pattern such that every leaf contributes a small increment to tree (stem) height, and every leaf axil has a flower bud that develops into a flower bunch. While the coconut palm is the most widespread tropical tree-crop as an overstory species in AFS, crop associations involving a variety of other palm species have also been described (Barford et al. 2015; Smith 2015). The single-stemmed and tall nature of most palms and their slender crowns make them particularly suitable as overstory species for not only shade-tolerant/adapted species but sun-plants such as cereals as well. As illustrated by the experience with coconut palm (Section 8.4), various intercrops can be grown during different stages of the palms' growth. Johnson (2011) classified and assessed the multipurpose nature of palms concerning their suitability for incorporation into tropical agroforestry development projects and identified a total of 52 such species. Numerous fruit- and nut-producing trees could also be combined with such palms. Table 8.2 shows major tropical palms grown in AFS in different places; the dominant among them include:

- Crop associations with arecanut (*Areca catechu*) palm in India (Nelliat and Bhat 1979; Bavappa et al. 1982; Figure 8.18)
- Peach-palm based agroforestry systems in Brazil and Central America (Clement et al. 2004; Smith 2015; Figure 13.A.I.9)
- Plantation crops in North East Brazil (Johnson and Nair 1984), and in Bahia, Brazil (Alvim and Nair 1986)
- Babassu palm (*Orbignya phalerata*) in Brazil (May et al. 1985)
- Intercropping with oil palm in Malaysia, West Africa, and Brazil (Figure 8.13 and 8.14)

Table 8.2 Major Tropical palms used in agroforestry systems

Scientific name	Common Name[a]	Distribution	Relevant species description and/or figures in this book
Areca catechu	Areca (Betel)	South and Southeast Asia	Figure 8.18
Bactris gasipaes	Peach (*Pejibaye*)	Central and S America	Chapter 13 (Appendix I; Figure 13.A.I.10)
Borassus flabellifer	Borassus, palmyrah	Brazil and other parts of S. America	
Cocos nucifera	Coconut	Pantropical, in coastal areas	The most ubiquitous palm of tropical coastal areas; known as "The tree of life." Figures 8.1, 8.2, 8.3, 8.20, 8.21
Elaeis guineensis	Oil	Pantropical; now widely cultivated in SE Asia	Figure 8.13, 8.14
Euterpe oleracea	Açaí (Assai)	South America	Figure 8.14; Chapter 13 (Appendix I; Figure 13.A.I.13)
Mauritia flexuosa	Mauritia	Brazil and other parts of S. America	
Metroxylon sagu	Sago	Southeast Asia	
Orbignya phalerata	Babaçu (Babassu)	Brazil and other parts of S. America	
Phoenix dactylifera	Date	Near- and Middle East; North Africa	

[a]Commonly the word "palm" is added to the listed names, e.g., areca palm, coconut palm, and so on

8.6.2 Multistory Tree Gardens

As mentioned in Chapter 7, several terms such as *multistory tree gardens, mixed tree gardens, and forest gardens* are used to refer to mixed tree plantations consisting of conventional tree/forest species and other commercial tree crops, especially tree spices, giving the system the appearance of a managed, mixed-forest. As opposed to homegardens that surround individual houses, these tree gardens are usually away from houses and are typically found on communally owned lands surrounding villages with dense clusters of houses, as in Indonesia (Java and Sumatra). Depending on the characteristics and conditions of the places where the systems are practiced, various forms of tree garden systems can be found. Some examples are:

- Tree gardens (*pekarangan* or *talun-kebun*) of Java (Wiersum 1982) and agroforestry garden systems of Sumatra (Michon et al. 1986)
- Compound farms (gardens) of southeastern Nigeria (Okafor and Fernandes 1987)
- Crop combination with cacao and other plantation crops in southeast Bahia, Brazil (Alvim and Nair 1986; Gama-Rodrigues et al. 2010)

Many characteristics and functions of all these tree-gardening systems are often similar, although their relative importance may change from one system to another. Wiersum (1982) lists the following common characteristics of tree gardens:

- The tree gardens are characterized by a large variety of mostly multipurpose plants in various vegetation layers (and sometimes animals, e.g., chickens), which provides for the effective utilization of environmental factors like water, nutrients, and sunlight. This variety ensures the production of different materials throughout the year.
- Most of the systems are dominated by perennial rather than annual crops resulting in a relatively high ratio of nutrients stored in the vegetation to those stored in the soil. This ensures an effective nutrient cycle and relatively little hazard for leaching and erosion. Effective nutrient status is further maintained by the uptake of minerals through deeply rooted perennials from deeper soil layers and effective retention of mineral inputs from rain and nitrogen fixation of leguminous species.
- Most tree gardens form a part of a whole-farm system that comprises annually cultivated fields used to produce staple, high-calorie foodstuffs (rice, maize, cassava), and the tree gardens used to produce highly nutritious supplementary products (proteins, vitamins, minerals), medicinal plants and spices, fuelwood, forage crops, and construction wood. Fruit trees also are an important component of the tree garden systems.
- Most tree gardens are used to produce a small, continuous flow of these supplementary products for subsistence and a possible small surplus for sale to local markets. Higher production and marketing levels may be attained in times of sudden necessities such as unfavorable climatic conditions or social necessities.
- Although the general cultivation practices are rather standardized, tree gardens vary with climate and soil, as well as with socioeconomic conditions.

The role of these tree gardens in food production will depend upon their species composition. In general, it is not as significant as that of homegardens. An important value of the tree gardens is their contribution to the general cash economy of the farmers through the sale of various (edible or non-edible) commercial products, e.g., timber, sawlogs, poles, and various fruits and spices. The tree gardens also have potential utility as efficient buffer zones around protected forests. The most significant contribution of tree gardens to food production will, however, be derived from the exploitation of the vast number of fruit trees in smallholder agroforestry systems (Figures 8.22, 8.23, and 8.24).

8.7 Concluding Remarks

Land-use systems consisting of tropical tree crops grown in association with other crops between or under them constitute a major form of agroforestry systems, more so in terms of their economic importance than the extent of area covered. Several of the tree crops included in this category have been developed for management as monocultural plantations during the colonial times and that legacy still lingers on, although significant proportions of some such crops are grown in integrated systems in smallholder farming systems. There is a mismatch between databases and management recommendations for the crops and the real-world situations such that available databases and production statistics may not be accurate, and the single-commodity oriented management recommendations may not be appropriate for the integrated production units. Indeed, systematic process-oriented studies on the role of shade trees on the growth and productivity of these high-value crops are meager, most reports and information being observational and experiential rather than experimental and quantitative. Multiple terms and nomenclature used for various forms of plant associations, such as intercropping, mixed cropping, multilayer-, multistrata-, and multistory cropping cause confusion to all concerned. Nevertheless, these agroforestry systems are receiving heightened attention nowadays in the context of the ecosystem services they provide and their potential role in climate change mitigation and biodiversity conservation on the one hand, and the illustration of crop substitution (coffee by cacao) necessitated to cope with the impact of climate change on the other.

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9 Silvopastoral Systems (SPS) in the Tropics and Subtropics

Contents

Abstract

Silvopasture is a broad term encompassing different forms of integrating trees, forage, and domesticated animals on the same unit of land. The practice ranges from the traditional, extensive animal grazing under woodlots and forests to modernized intensive forms of tree–animal integration. These can broadly be grouped under two categories: grazing system where cattle graze on pasture under scattered or systematically planted stands of trees; and the browsing (tree-fodder) systems, in which the animals are usually stall-fed with fodder from trees or shrubs grown on farms and farm boundaries. Most silvopasture systems (SPS) in Africa, South Asia, and other developing regions of the world involve extensive open grazing by free-roaming animals under natural stands of trees and shrubs. Major examples are found in the so-called Parklands of sub-Saharan Africa, the Brazilian *Cerrado* (wet savanna) and *Caatinga* (dry savanna) biomes, and the arid and semiarid lands of the Indian subcontinent. The browsing systems of small-

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scale dairy farming involving cut-and-carry fodder from fodder banks and boundary plantings are a popular and traditional means of livelihood strategy and income generation in rural households. The integrated crop-livestock-forestry system is a relatively new form of silvopastoral activity organized on a commercial scale in Brazil and some other parts of Latin America. Research on SPS in the tropics and subtropics has so far been more exploratory than experimental, with emphasis on understanding and documenting the existing situation. Thus, the literature on tropical SPS is dominated by conventional system descriptions, reports on species inventory and evaluations, nutritive values of indigenous tree fodder, and sociocultural narratives of the people and their traditions.

9.1 Introduction

Silvopasture is the agroforestry practice of integrating trees, forage, and livestock on the same land-management unit. The age-old practice of forest grazing (grazing under woodlots and forests by domestic animals) is considered the earliest example of the integration of trees and pasture for livestock production. Although the improvements in such traditional practices in the tropics over time have been relatively few, commercial silvopasture involving improved forage species (grasses and legumes) and tree-planting-and management operations based on research results has made impressive progress in several temperate countries and some tropical and subtropical regions during the past few decades. Thus, as in the case of most other types of land-use systems, silvopasture is practiced at varying levels of management intensity and technical input, ranging from extensive, often uncontrolled grazing systems in open lands and forests to high-intensity tree + animal management systems. Generally, the former type of low-input management and extensive grazing predominates in the resource-poor tropical and subtropical conditions, and the high-intensity management systems in the industrialized countries. Today, silvopasture is a broad term encompassing different variants of this traditional practice as well as vastly modernized forms of the tree–animal integration. Following a brief narrative of some general characteristics that are common to all forms of silvopastoral systems (SPS), this chapter will focus on tropical and subtropical SPS that are mostly noncommercial operations (except for the commercial SPS in Brazil and southern parts of South America). Salient aspects of commercial SPS in industrialized regions will be presented in Chapter 10 (Temperate Agroforestry Systems).

9.2 Tropical and Subtropical SPS: An Introduction

In many developing regions of Asia, Africa, and parts of Latin America, domestic animals that produce milk and meat and provide draft power for farm operations are an essential component of the farming system and livelihood strategy. In those conditions, a farm family's wealth is often expressed in terms of not only the area and productive capacity of the farmland but also the size and composition of its animal herd (Figure 9.1). Various types of trees and shrubs are a major source of animal feed in such situations. For example, India has a cattle population of 186 million, 12.65% of the world's total (FAO 2017), a vast majority of which depend on fodder from trees and shrubs grown mostly on farmlands and farm boundaries (Figure 9.2). It is also well recognized that uncontrolled grazing in forests and communal lands has caused severe soil erosion and ecosystem degradation around the world. On the other hand, the well-designed and properly executed commercial silvopasture operations of today provide enhanced soil protection and other forms of environmental benefits and increased long-term income from the simultaneous production of trees and animals. In such situations, the trees provide shelter for animals and can boost understory herbage production by adding nutrients – especially nitrogen – to the soil and enhance soil carbon storage; and typically,

Figure 9.1 Cattle are an essential component of farming systems and a symbol of wealth in many traditional societies. (Photo: PKR Nair 1997, Chhattisgarh, India)

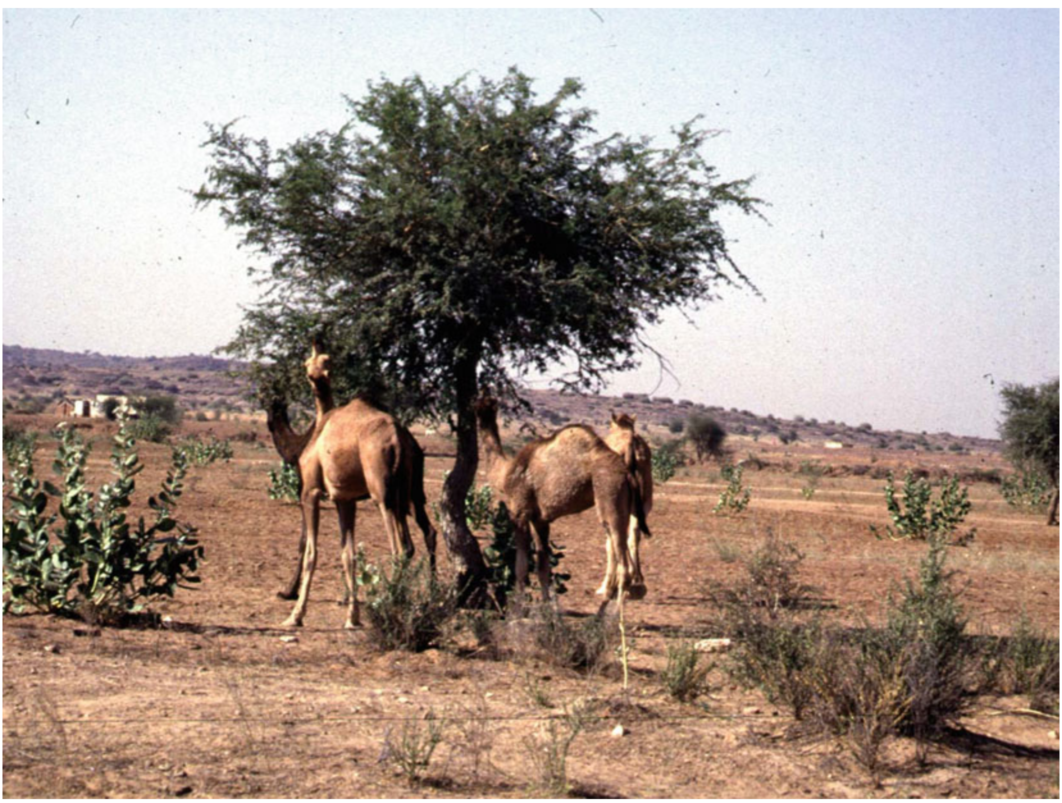

Figure 9.2 Trees are a source of animal fodder in dry regions around the tropics: camels grazing on *Prosopis cineraria* trees in Rajasthan, India. (Photo: PKR Nair 1985).

the trees are selectively harvested for their wood or used to produce other products.

According to FAO statistics (FAO 2017), grasslands extend over about 3 billion hectares globally with roughly two-thirds in the tropics and one-third in the temperate regions; silvopasture is a major land-use system in about 450 million hectares and has the potential to be extended over larger areas. Besides the traditional forest grazing around the world, numerous forms of combined production of trees and animals from the same land management unit have been followed in many parts of the tropics for a long time. These include intimate integration of multipurpose trees and shrubs – some of which sprout back (coppice) vigorously after pruning – that produce nutrient-rich tree fodder with other production components of the complex farming system for feeding small herds of milk-producing farm animals reared in homegardens and other smallholder farms. Such integrated production systems are important components of livelihood strategies of countless numbers of resource-poor farmers but are seldom recognized, let alone appreciated, as SPS.

9.3 Common Forms and Terms of Silvopasture

Silvopasture being a traditional practice with a long history, it is only natural that various forms of the practice and location-specific terms and operations are prevalent in different places. Nevertheless, all forms of silvopasture can broadly be grouped under two categories: grazing systems and tree-fodder systems. In the grazing systems, cattle graze on pasture under scattered stands of trees or widely spaced – mostly planted – trees (Figures 9.3 and 9.4). In the tree-fodder systems, the animals are either stall-fed with fodder from trees or shrubs grown on farms and farm boundaries or are let to do controlled browsing of such trees (Nair 1993; Nair et al. 2008). The underlying principle and motivations of all such practices, however, are common. The principle is that multispecies combinations could result in better utilization of natural resources of solar energy, soil, and water. The motivations for adopting the practice are financial and opportunistic: more production leads to better economic

Figure 9.3 Livestock grazing under natural stands of trees is a common land-use system in many dry regions of the world especially in the tropics and subtropics. (Photo: ICRAF/World Agroforestry)

Figure 9.4 Livestock grazing under natural stands of trees, Niger. (Photo: ICRAF/World Agroforestry; http://blog.worldagroforestry.org/wp-content/uploads/2014/01/parklands-Niger-FAO.jpg)

returns, and it makes perfect sense to make use of the available opportunities.

While the grazing system is practiced throughout the world, the browsing (tree-fodder) system is a common feature of the smallholder farming practice in the tropical regions as mentioned above, and virtually non-existent in the industrialized regions. Consequent to the realization in the 1970s and 1980s that the need for fodder (as well as fuelwood and small timber) was a major reason for tropical deforestation, the tree-fodder system received considerable scientific attention during the early stages of agroforestry development. That led to the recognition, for the first time, of the importance of fodder trees in animal agriculture and thus agroforestry. The grazing form of silvopasture, however, is the most common and widely practiced agroforestry system in the industrialized regions, and it has gained added prominence, thanks to the relatively higher research support, since the turn of the 1990s (see Chapter 10). Furthermore, with the recent emphasis on the environmental impact of land-use systems, the role of silvopasture and other agroforestry practices in mitigating climate change through carbon (C) sequestration has been a major area of research focus (see Chapter 20). Additional benefits of silvopasture include water quality improvement (Michel et al. 2007), soil conservation, aesthetics, and providing shade to cattle. Thus, silvopasture is considered highly compatible with traditional ranching and includes several elements of best management practices for ranchers in North America (Garrett 2009).

Most silvopasture systems in Africa, South Asia, and other developing regions of the world involve extensive open grazing by free-roaming animals under scattered natural stands of trees and shrubs mostly in semiarid to arid areas. A typical example is the so-called Parklands of sub-

Saharan Africa (Section 9.4.2). More intensive and controlled grazing systems of silvopasture are practiced in Latin America where animals are penned in parcels of land with barbed-wired living-fence, and grazing is regulated (Somarriba et al. 2012). Such organized SPS are popular in the extensive Cerrado region of Brazil, too (Nair et al. 2011). Open grazing by free-roaming animals, however, is still common in many arid and semiarid regions of the world, such as the Caatinga region of Brazil (Pinheiro and Nair 2018) and dry parts of India (Tejwani 1994). Cattle grazing under coconuts and other plantation crops is a traditional silvopastoral practice that is still followed in Asia and Oceania (Chapter 8, Section 8.6). The most labor-intensive SPS is the stall feeding of animals by fodder from trees grown elsewhere, which is a common practice in smallholder farming systems of South Asia and Africa (Kiptot and Franzel 2012); these are described in some detail in Section 9.5. Some of the common noncommercial SPS around the world are described briefly in the following sections.

9.4 Common Silvopastoral Grazing Systems in the Drylands

Drylands consisting of hyper-arid, arid, semiarid, and dry subhumid categories of the aridity index† classification, occupy about 60 million km^2 or more than 40% of the earth's land area [†Aridity index is a numerical indicator of the degree of dryness of the climate at a given location for characterizing regions that suffer from a deficit of available water for effective use of the land for agriculture (https://en.wikipedia.org/wiki/Aridity_index)]. Out of the 2 billion inhabitants of the drylands, about 90% live in developing countries and are relatively more dependent on natural resources than other groups of populations. Tropical drylands are more exposed than other ecological regions to the threat of environmental degradation, with vast areas, estimated as 6 million to 12 million km^2, affected by desertification, reducing their capacity to sustain human livelihoods (MEA 2005). Agrosilvopastoral systems consisting of intercropping under scattered trees with various food crops during the usually short rainy seasons and animal rearing through extensive, often free-roaming, grazing during long dry seasons are the most common land-use system in these areas. The types of systems and their species composition and management operations vary in different places according to local traditions and ecoclimatic conditions. General features of these dryland SPS in arid and semiarid parts of three major geographical regions (West Africa, Northeast Brazil, and Western and Central India) are presented here.

9.4.1 The Parkland System of West Africa

The Agroforestry Parklands, commonly known as the Parklands, constitute the predominant agroforestry system in semiarid West Africa and some other parts of sub-Saharan Africa. Included in the general category of "multipurpose trees on farmlands" in ICRAF's Agroforestry Systems Inventory (Nair 1985) and known by various names such as tree savanna, savanna parkland, and *parcs arborés*, the term refers to the traditional system where various multipurpose trees are planted or protected and nurtured on cropping and grazing lands (Boffa 1999). Parkland attributes include a regular distribution of relatively even-aged trees or shrubs and a low tree density with discontinuous tree cover (Figures 9.5, 9.6 and 9.7). The name Parkland is derived from the resemblance to urban or rural recreational parks with large scattered trees over expanses of grass. Although the system is prevalent predominantly in the vast semiarid regions of West Africa, it is also found in the Sudan zones as well as in southern Africa (Botswana, Malawi, and Zimbabwe). Several variants of the practice are found in different countries, but they all represent agrosilvopastoral intercropping systems under a stand of scattered trees. Except when the land is under food crops grown during the short rainy seasons (3–4 months a year), animal grazing – usually uncontrolled open grazing – is the practice during the ensuing long, hot, dry season.

Figure 9.5 Scattered stands of trees, called parklands, are a common feature of the drylands of sub-Saharan Africa, especially in West Africa (see Chapter 5). The photo, from Mali, shows a typical stand of *Faidherbia albida* trees in the dry season when the trees have green foliage when all the other vegetation is dry. (Photo: ICRAF/World Agroforestry)

Figure 9.6 West African parklands (see also Chapter 5). (Photo: ICRAF/World Agroforestry; http://old.worldagroforestry.org/wadrylands/images/sahelianParkland.jpg)

Figure 9.7. A stand of *Faidherbia albida* trees with new foliage that starts appearing at the beginning of the dry season. See also Figures 5.10 and 5.11

Depending on the seasons, the vast landscapes will look very different during the rainy (cropping) and dry (grazing) seasons: lush green foliage of crops under scattered stands of trees during the former and extremely dry scenes with very little vegetation during the latter. The contrast is more striking with the *Faidherbia albida* trees that have the remarkable phenology of the trees losing leaves in the rainy season (Figures 9.8 to 9.10) and being covered fully with a canopy of leaves during the dry season when everything else is dry and brown. The common trees in the parklands (Table 9.2) are included in the MPT species profiles of Chapter 13, Annexure 13-I). The trees are seldom planted but sustained by natural regeneration. The comprehensive account of the Parkland system by Boffa (1999) published as FAO Conservation Guide number 34 is still an authoritative and widely quoted reference manual.

Agroforestry parklands are also a major source of wood and nonwood products, which provide significant household income that is very important for the local economies. Shea butter from the nuts of the shea tree (*Vitellaria paradoxa*), a common tree in the parklands (Figure 9.11), for example, has gained considerable importance lately with excellent export earning potential for several nations in the Sahel. On the other hand, the decline in the trade of gum arabic produced from *Acacia senegal* (Figure 13.A.I.3: Chapter 13, Appendix I) a major component of the parklands in the Sudano-Sahelian zone, has seriously impacted the national economies of the countries of the region. In some places in West Africa, agroforestry parklands account for up to 75 percent of total harvests of wood and non-wood products (Boffa 1999). Parkland resources are of considerable social and cultural significance too. Specific social groups, including women and the poor, tend to be particularly involved in the gathering and sometimes the processing of parkland products.

Although frequently dominated by just one or a few species, the parklands have contributed to the maintenance of numerous species. Scattered trees also fulfill fundamental ecological functions in soil and water conservation and environmental protection. Most of the agricultural production in the Sahel where there are settled populations occurs under the discontinuous cover of parkland trees. In several instances in arid and semiarid

Figure 9.8 The *Faidherbia albida* tree that is common in the West African Sahel has a unique phenology: it is leafless during the rainy season, which allows farmers to grow a variety of crops under or between the trees. The photo shows a leafless tree with a crop of cotton underneath in Mali. (Photo: PKR Nair)

Figure 9.9 Cattle seek shade and shelter under the canopy of *Faidherbia* (syn. *Acacia*) albida trees that have foliage during the extremely hot and dry season in the drylands of sub-Saharan Africa. (Photo: ICRAF/World Agroforestry)

regions, the *screen function* of trees is also evident. Human beings and livestock seek shade during mid-day when outside temperatures soar to more than 40 °C. In the degraded rangelands of the arid and semiarid regions, herbage yields under shade are usually much higher (up to twice or more) than that in the open, and the grass remains greener for 4 to 6 weeks more at the end of the rainy reason. The reason is that the intensity of solar radiation and wind speed is reduced in the tree+grass system compared to the open systems (sole grass), which in turn, reduces the potential evapotranspiration (PET) losses. Experimental studies in the semi-arid region of Botswana (southern Africa) showed that under the canopy of trees such as weeping wattle (*Peltophorum africana*), umbrella thorn acacia (*Acacia tortilis*), and raisin bush (*Grewia*

Figure 9.10 A "poster photo" of agroforestry showing maize under *Faidherbia albida* that is leafless during the rainy (crop-growing) season. (Photo: ICRAF/World Agroforestry)

Figure 9.11 *Vitellaria paradoxa*, the shea butter tree, is another common tree in the Agroforestry parklands of West Africa. (Photo: ICRAF/World Agroforestry)

flava), solar radiation and wind speed were reduced by about 50% and PET by about 70%, compared to the adjacent open area (Houerou 1987). Thus, the agroforestry parkland system is of considerable economic, ecological, and socio-cultural importance for the entire Sahelian region and the semi-arid southern Africa.

9.4.2 SPS in the Semiarid Brazilian Tropics

The Cerrado. Savannas are a major component of the world's vegetation, covering one-sixth of the land surface and accounting for 30% of the primary production of all terrestrial vegetation (Grace et al. 2006). The Brazilian savanna, known as the *Cerrado*, occurs mainly in the central Brazilian states and extends over 200 million ha (Batlle-Bayer et al. 2010). The Cerrado is a wet savanna consisting of a gradient of physiognomies from grassland (called "*campo limpo*") to a sclerophyllous (sclerophyll = a woody plant with hard evergreen leaves and short internodes) forest (*Cerradão*), with over 10,000 species of plants, of which 45% are unique. The region's typical climate is hot, semi-humid, with pronounced seasonality marked by a dry winter season from May through October. The annual rainfall ranging from 1200 to 2000 mm occurs during the summer (known, rightly, as the rainy) season between October and April, and the mean annual temperature varies from 22 °C in the south to 27 °C in the north. The Cerrado trees have characteristic twisted trunks covered by a thick bark and leaves that are usually broad and rigid.

The region has been the focus of intense agricultural expansion since the 1960s, and a large area of native vegetation has been replaced by agriculture, pastures, and planted forests (EMBRAPA CERRADO 1999; The Economist 2010 (http://www.economist.com/node/16886442). Cultivated pasture areas, estimated to range from 35 million to 50 million ha (Sano et al. 2000), account for the largest agricultural expansion, mostly with the introduction of the African grass of the genus *Brachiaria*. Most of these cultivated pastures have, however, experienced some degree of degradation; they have lost, to varying extents, their capacity to produce biomass due to deterioration of soil chemical, physical and biological conditions. Various types of landholdings and producers can be found in the Cerrado biome, ranging from large farms with areas of more than 20,000 ha and a variety of crop fields or cattle, to a large number of "small" farms with areas less than 100 ha. Large tracts of the Cerrado have also been planted to fast-growing trees, especially eucalyptus hybrids (*Eucalyptus* spp.) and pines (*Pinus* spp.), which account for roughly two-thirds and one-third, respectively, of the approximately 5.5 million ha of planted forests in Brazil (ABRAF 2008). Most of these plantations were established on small farmlands that used to raise cattle. This new development, motivated primarily by its monetary advantages, has brought up two major issues: the introduction of non-native tree species in the biome, and the decline – if not elimination – of the traditional activity of cattle raising. Integrating cattle and trees as in silvopastoral systems offers the advantages of monetary benefits from planted forests and supports traditional cattle rearing. Additionally, there are advantages via soil carbon sequestration (see Chapter 20).

Silvopastoral systems in the Cerrado are mostly of the commercial type. First established in the Minas Gerais State in the late 1900s, the area under the practice has been increasing steadily since and has extended to other areas of the Cerrado, mainly in the state of Mato Grosso do Sul. It is perceived (Dubé et al. 2000) that the establishment of silvopastoral systems can reduce the cost of establishment of the whole (beef + timber) system; furthermore, the additional income derived from the crops would be an economic incentive to tree-plantation owners during the early years of plantation establishment. The system is established by cultivating one or two annual crops in rows in between the widely-spaced tree rows Eucalyptus (hybrid), the most common tree used in the system, is planted at varying row spacings, the most common being 10 x 4 m or 8 x 4 m (Figures 9.12 and 9.13). Tree

Figure 9.12 Commercial silvopastoral systems, using *Eucalyptus* hybrids, have become popular in the semiarid Cerrado region of Brazil and elsewhere in Latin America. (Photo: PKR Nair 2008)

Figure 9.13 The most common grass species used in commercial silvopastoral systems in Brazil, as shown in Figure 9.12 is *Brachiaria brizantha*. After establishing eucalyptus, crops such as rice (*Oryza sativa*) and soybean (*Glycine max*) are cultivated in the first and second year, respectively. In the third year, seeds of *B. brizantha* is sown to constitute the understory. Sixty days after sowing the grass seeds, beef cattle are stocked in the area for grazing. (Photo: PKR Nair 2008)

rows are usually aligned in the east-west orientation to allow the highest extent of light availability to the understory grass between trees. Most planters limit the soil preparation for the silvopastoral establishment to the minimum, mainly spot application of herbicides to kill weeds in the rows where the trees would be planted. This minimum soil preparation is important to avoid soil disturbance and oxidation of soil organic matter. Soil moisture availability and mild temperature under trees create better conditions for mineralization of nitrogen which contributes to improving and extending the forage quality in the dry season. Crops such as rice (*Oryza sativa*) and soybean (*Glycine max*) are cultivated in the first and second year, respectively, after establishing eucalyptus. In the third year, seeds of the grass *Brachiaria brizantha* is sown to constitute the understory. Sixty days after sowing the grass seeds, beef cattle are stocked in the area for grazing. Several research studies on management aspects of the system such as planting configuration and stand density of trees and the use of forage legumes as a means to reducing nitrogen fertilizer application have been reported (Silva 2008; Nair et al. 2010; Tonucci et al. 2011).

The Caatinga Biome of Northeast Brazil. Extending over about 850,000 km^2 in ten states and located between 3° to 17° S, and 35° to 45° W (IBGE 2004), the Caatinga has some of the most complex bio-climatological features. The rainfall is highly erratic varying in the range of 260–800 mm per year; the rainy season lasts 3 to 5 months, and severe droughts lasting 3 to 5 years occur every three or four decades (Fernandes 2003). For the inhabitants of the region (more than 25 million), the main livelihood options are livestock and crop production. The most common vegetation includes trees and shrubs belonging to the botanical families Cactaceae, Caesalpinaceae, Mimosaceae, Euphorbiaceae, and Fabaceae, the major genera being *Senna*, *Mimosa,* and *Pithecellobium*. The most common woody species are *Amburana cearensis*, *Anadenanthera colubrina*, *Aspidosperma pyrifolium*, *Caesalpinia pyramidalis*, *Croton* spp., *Commiphora leptophloeos*, and *Mimosa* spp. Examples of fodder trees retained by farmers in the Caatinga include: *Bauhinia forficata, Caesalpinia ferrea*, and *Mimosa caesalpiniaefolia* (Prado 2003). Overgrazing and intense firewood gathering account for about 45% of deforestation and desertification in many parts of the region (MMA 2007, 2011). Pinheiro and Nair (2018) suggested opening up the overstory canopy, coppicing to facilitate the production of fresh and abundant forage for animals, enrichment planting with desirable tree and understory species, and introduction of unconventional feed sources such as cactus (*Opuntia ficus-indica)* as the opportunities for enhancing the low carrying capacity of the Caatinga region.

9.4.3 SPS in the Arid and Semiarid Parts of India

As mentioned in the introductory paragraph of this chapter, India has a large cattle population, estimated as 186 million or 12.65% of the world total according to FAO Statistics 2018 (Section 9.2 of this chapter). The Government of India statistics (BAHS 2017) estimate the total livestock (cattle, buffalo, goats, etc.) population of the country as 512 million including 190 million cattle. Estimates about the area under silvopasture in India also vary, because different forms of SPS are practiced on lands categorized as under agriculture, forestry, range management, etc. The vast majority of the animals are maintained in subsistence, low-input grazing systems on permanent pastures and other grazing lands, mostly under scattered trees. Although climatically the country is predominantly tropical and subtropical, some temperate meadows and pastures occur at elevations above 2000 m in the eastern and western Himalayan regions.

Trees and shrubs are an integral part of most grazing lands in India, and they support animal production both directly through the provision of fodder and shade and indirectly through maintenance of soil quality and protection. Thus, most grazing systems in India are examples of silvopastoralism. Several variants of the practice exist;

Tejwani (1994) classified them into two broad categories: Pastoral silviculture and Silvopastoral practices. The former includes grazing lands with scattered trees with animal grazing as the principal activity; the types of grasses and trees vary with regional agroecological conditions. Some of the well-known examples are the grassland and tree management systems in the arid region in and adjoining the state of Rajasthan (Figure 9.14) and the Deccan plateau (Figure 9.15). The other category, silvopastoral practices, involves lopping of trees and feeding the foliage to animals as well as grazing on the understory grasses and bushes in forestlands or plantations across the country. Nomadic pastoralism, a traditional form of human-livestock-grassland interaction, is also practiced in the drylands of western India, the Deccan Plateau, and in the mountainous reaches of the Himalayas (Roy and Singh 2013). Grazing or harvesting of forage crops grown in association with planted trees constitutes another subset of silvopastoralism. The differences between the two categories (Pastoral silviculture and Silvopastoral practices), however, are not rigid and the terms are often used synonymously. Considering the geographical diversity and vastness of India, it is only natural that numerous types of tree- and grass species occur in different agroecological regions of the country. The Indian agroforestry literature is also replete with details of the production potentials of a wide array of tree+grass combinations under varying ecoclimatic conditions (Figure 9.16).

In the arid rangelands in the western part of the country in and adjoining Rajasthan, farmers have been practicing traditional farming systems in which domesticated livestock are integrated with

Figure 9.14 Animal grazing on the grass under natural (scattered) or planted stands of trees is a common form of silvopasture in the dry (arid and semiarid) regions of the Indian subcontinent. The photo shows sheep grazing on the grass *Cenchrus ciliaris* under a stand of *Hardwickia binata* trees in Rajasthan in northwestern India. (Photo: M. Patidar, CAZRI, ICAR, India)

Figure 9.15 The *Kangayam* system, a silvopastoral system similar as in Figure 9.12: Mecheri sheep grazing on *Cenchrus ciliaris* under *Acacia leucophloea* trees in Tamil Nadu, India. (Photo: N. Biradar, ICAR-IGFRI, India)

Figure 9.16 The Central Arid Zone Research Institute (CAZRI: www.cazri.res.in), Jodhpur, Rajasthan is a leading Indian government research institution with a long record of productive research in silvopastoral and other agroforestry practices in the drylands. The photo shows a field experiment of *Prosopis cineraria* (the "*khejri*") trees and various understory forage species. (Photo: Archana Verma, CAZRI)

natural ecosystems (Tewari and Arya 2005). Free grazing in the common pasturelands has been a dominant survival strategy for the landless farmers in this region for a long period (Roy and Singh 2013), which makes the system similar to the Parkland system of West Africa described in Section 9.4.1. Overgrazing by small ruminants like goats and sheep, however, is a major problem of the grazing systems in these economically poor and climatically hostile regions.

Khejri, a well-known term in land-use of the drylands of Rajasthan, is used to refer to both the tree (*Prosospis cineraria)* and the wide-spread land-use system where the trees are deliberately nurtured and interplanted with millets and legumes on farmlands, and the trees are lopped and fed to farm animals (Mann and Saxena 1980; Tejwani 1994). Known as the "king of the desert," *P. cineraria* is a sacred tree for a large number of people in Rajasthan, and every part of the tree from foliage to pods and wood is utilized. Various aspects of the *khejri* system have been investigated and reported in numerous studies since the 1970s (Mann and Saxena 1980). Wild jujube (*Zyziphus nummularia*) (Figure 13.A.I.22) is another important tree species in the pastoral-silvicultural system of this region; other similar examples include *Acacia nilotica, A. tortilis,* and *Ailanthus excelsa,* known as the Indian tree of heaven (Shankarnarayan et al. 1987).

Kancha is another traditional, low-input, grassland- and tree management system practiced widely in the semiarid tropics in the Deccan plateau of southern and south-central parts of India. The region has an elevation of 300 to 1000 m and a mean annual rainfall of 500 to 1300 mm (Tejwani 1987). The *kancha* is a controlled grazing system, in which the land is left fallow for periods of 1–3 years. During this phase, the existing trees are protected from biotic pressures, which results in the development of natural succession of grasses in the *Sehima-Dichanthium* grassland type, attaining maturity in 4–10 years depending on the location and site conditions. Several tree species are retained in the kanchas, including *Eucalyptus tereticornis*, *Casuarina equisetifolia*, *Borassssus flabellifer*, neem (*Azadirachta indica,* and *mahua* (*Madhuca longifolia*) (Tejwani 1987). Fruit trees such as custard apple (*Annona reticulata*), mango (*Mangifera indica*), ber (*Ziziphus mauritiana*), and tamarind (*Tamarindus indica*) are also common, their fruits being collected for home consumption; fruits of neem and *mahua* are collected for sale and *mahua* fruits are used for extracting the edible oil and its flowers used to brew an alcoholic drink.

A remarkable example of silvopastoralism is practiced by the nomadic communities in the western and central Himalayas (including the cold desert areas). Animals graze in the alpine pastures during the summer and are then moved down to the temperate forests with the onset of cold weather and eventually into the subtropical forests situated in the lower reaches (Tejwani 1994). The dominant grass species found in the alpine meadows is oat grass (*Danthonia cachemyriana*); other grasses of the genera *Agrostis, Bromus, Briza, Calamagrostis, Festuca,* and *Poa* are also common (Chandran 2015). The temperate zone supports forests of deodar (*Cedrus deodara*), and Himalayan cultivars of the genera *Abies* (fir), *Acer* (maple*)*, *Betula* (birch), *Picea* (spruce), *Pinus* (pine), and *Quercus* (oak).

As in the case of dryland silvopastoral systems in other tropical regions of Africa and Latin America, the silvopastoral systems in the drylands of India, too, represent a low-input, traditional land-use system that has been practiced for long by the local inhabitants, who are generally poor and have little or no social or political power. No wonder, then, that practically no organized efforts have been made to study and improve the systems. The Green Revolution and such other technological advancements have had no impact on these forgotten and ignored systems and their practitioners. The information base on the system is patchy and limited to some descriptions with listings of common species. Given the large areas that are covered by these systems, it is not unlikely that the systems, hopefully, will one day attract deserving attention for improvement.

9.4.4 Other SPS in the Semiarid Regions Worldwide

In the Middle East and the Mediterranean, the most widespread SPS is the Dehesa system in the oak woodlands of Spain and Portugal, estimated to cover more than 3 million ha (Mosquera-Losada et al. 2012; Moreno and Pulido 2009 (see Chapter 10, Section 10.4.1 for details of this system). Open woodlands in other Mediterranean countries are also used as SPS, with either oaks or carob trees (*Ceratonia siliqua*). Various intercropping systems, including silvopasture with olive trees (*Olea europeaea*), are also very common in the Mediterranean, especially Greece (Papanastasis et al. 2009) and Portugal (Castro 2009). In Chile, silvopasture system management practices include fodder banks, grazing in croplands, family gardens; but due to the high aridity in many regions, only a few forage/food-producing tree species survive, *Acacia saligna, Prosopis tamarugo*, and *P. chilensis* being the most common (Rojas et al. 2016). These species are also common in the salt-affected soils and severely degraded arid regions in Peru, Bolivia, and Argentina. Throughout the arid and semiarid regions of these countries, these tree species are used in reforestation projects as well as a variety of other land-use systems, including degraded-land reclamation, soil-erosion control, and supplemental human food items so that the system may not strictly be SPS (Rojas et al. 2016; Peri et al. 2016).

In East and Central Africa, the silvopastoral systems are dominated by different species of the genus *Acacia* in the arid parts of Kenya, Somalia, and Ethiopia; protein bank (cut-and-carry) and fodder production are also very common. Numerous reports are available on this and similar extensive SPS in the region (Garrity et al. 2010). Overall, the general socioeconomic conditions of the regions and the countries concerned are the main factors that influence the nature of system management. Thus, in Africa and the Indian subcontinent, the SPS systems are more subsistence-oriented and labor-intensive than in the Mediterranean and southern regions of South America, where the system management is more capital-intensive and less labor-intensive.

9.5 The Browsing Systems: Tree Fodder and Fodder Trees

Small-scale dairy farming has been a popular and traditional means of livelihood strategy and income generation in many rural households throughout the tropics. Numerous reports are available on the extent and importance of the practice as well as the various types of practices in different parts of the world. All of them involve using foliage of forage species to feed the animals by either letting them browse the plants or transporting the fodder to the animals in their sheds or stalls. Several trees and shrubs are valuable sources of animal feed, and tree fodder (a common name for forage obtained from fodder trees and shrubs) is a major component of animal feed in such smallholder animal production systems. Fodder trees and shrubs are a basic component in almost all such practices. A significant addition to this information base is provided in a new publication "*Alternative animal feeds from agroforestry plants,*" a special issue of the journal *Agroforestry Systems*, volume 94, issue 4, August 2020. It contains 50 articles that report a variety of information on the role, nutritive value, chemical composition, management, etc. of several plants (trees, shrubs, and herbs), some well-known and others little-known in agroforestry and SPS, from different parts of the tropics. Profiles of the major fodder trees and shrubs that are used widely in tropical SPS are included in the multipurpose (MPT) Species Profiles in Chapter 13 (Annexure 13-I), and various terms used to denote the tree-management practices for fodder production in SPS are presented in Tables 9.1 and 9.2.

Table 9.1 Some Common Terms Used in Silvopastoral Literature

Boundary Planting: Refers to planting trees as a boundary demarcation between two farms (or fields on the same farm), as a **buffer** between roads and farms. Trees in the boundary provide fodder, fuelwood, poles and timber, and services like windbreaks and soil erosion control in addition to protection and privacy to the farm/plot.
Cut-and-Carry System: Also known as zero-grazing, cut-and-carry is an animal feeding practice followed by smallholder dairy farmers, in which the fodder (leaves and small branches) obtained by pruning the trees and shrubs is carried and fed to animals kept in sheds or stalls. It is called cut and carry because the fodder is brought to the animal, not the animal to the fodder.
Fodder Bank: An assemblage of tree and shrub species that are predominantly fodder species, but are multipurpose in nature, providing multiple products and services such as forage, fruits, soil fertility improvement, and biodiversity habitats. They can be assembled as woodlots, live fences, windbreaks, soil conservation barriers, and for similar other purposes. Usually, the fodder is cut and carried to stall-feed the animals, but sometimes are allowed to graze on the fodder bank in a controlled manner for defined periods.
Hedgerows: Trees and shrubs that can withstand repeated pruning planted close together to form long vegetative barriers of varying thickness and height. Hedgerows that used to be a common feature of agricultural lands as boundary markers have gradually been removed to allow the use of farm machinery. Depending on the tree or shrub species used, traditional hedgerows provide many benefits including forage and browse for livestock or for soil fertility improvement in tropical alley cropping (Chapter 6), and food and medicinal plants for rural populations.
Live (Living) fence: Live fences consist of trees planted on property lines that serve as poles for establishing barbed-wire fence-lines. They are common as boundary markers between paddocks in silvopastoral systems, especially in Central American countries.
Open grazing**:** Uncontrolled grazing by free-roaming anmals.
Pannage: A practice dating from Roman times, in which pigs are released into beech and oak woodlands to feed on the acorn and beech mast, and into fruit orchards to eat fallen fruit. The term is not used much in current literature.
Pollards/Pollarding: The practice of cutting branches from trees two to three meters above ground level to obtain leaf fodder for feeding livestock and/or wood for fuel or other uses; a common practice in both temperate and tropical forestry and agroforestry. See Figure 14.3 for the explanation of common tree management terms.
Shelterwoods (Temperate Regions): Mature woodlands providing shelter to cattle and sheep during winter months
Stall feeding: Feeding animals retained in sheds or pens with fodder cut and carried from nearby stands of trees and shrubs.
Wood-pasture (Mostly in Temperate Regions): Remnants of old woodlands with a widely scattered stand of trees and associated biodiversity in the temperate regions especially in Europe and the UK, some of them with historical and cultural values, e.g., the New Forest in southern England.

9.5.1 The Cut-and-Carry System

It is called the cut-and-carry system because the fodder is brought to the animal, not the animal to the fodder (Figure 9.17). Along with Fodder Banks (Section 9.5.2), cut and carry is a common aspect of traditional, smallholder farming systems (Figures 9.18 and 9.19). Unlike in drylands, extensive grazing is not an option in smallholder farms in humid and subhumid tropics, where most family-farms are small (less than 2 ha), and managed communal grazing lands are almost non-existent anymore. The successful eradication of the tsetse fly (a collective name for 23 species of the fly of the genus *Glossina* that are biological vectors of trypanosomes, which cause human sleeping sickness and animal trypanosomiasis) in the late 1990s provided an incentive to adopt cut-and-carry fodder production for enhanced animal-farming opportunities in smallholder production systems in Africa. More farmers established small dairy units in their backyards and began cultivating grass-legume plots to feed their dairy cows. For example, in Zanzibar islands of Tanzania the number of households that kept improved dairy cows increased steadily from 2.4% of the total livestock keepers' pre-tsetse eradication to 23.5% in 2002, whereas the proportion of crossbred cows also increased from 2% of the total cattle population in 1993 to 5% in 2003. On average, 52% of the typical small-scale dairy households in Zanzibar, each with seven to eight family members, kept four to five head of cattle and described livestock keeping as their

Table 9.2 Common trees in the West African Parklands[a]

Scientific name	English name	French name
Acacia senegal	Gum arabic	Gommier
Adansonia digitata	Baobab	Baobab
Anogeissus leiocarpus		Bouleau d'Afrique
Balanites aegyptiaca	Desert date	Dattier du désert
Bombax costatum	Red flowered silk cotton	Kapokier rouge
Borassus aethiopum	Fan palm	Rônier
Ceiba pentandra	Silk cotton	Fromager
Diospyros mespiliformis	Ebony	Faux ébenier
Elaeis guineensis	Oil palm	Palmier à huile
Faidherbia albida (syn. *Acacia albida*)	Winterthorn	Kad, Faidherbia
Hyphaene thebaica	Dum palm	Palmier doum
Lannea microcarpa		Raisinier
Parkia biglobosa	African locust bean	Néré
Sclerocarya birrea	Marula	Prunier
Tamarindus indica	Tamarind	Tamarinier
Vitellaria paradoxa (syn. *Butyrospermum paradoxum*)	Shea nut tree	Karité, arbre à beurre
Vitex doniana	Black plum	Prunier noir
Ziziphus mauritiana	Jujube	Jujubier

[a]See Annexure 13-I, Chapter. 13, for short species profiles of selected species

Figure 9.17 Stall-feeding of animals penned in sheds with grasses and tree fodder cut from trees or shrubs grown on farms and farm boundaries (the "cut-and-carry" type of silvopastoral practice) is common in many smallholder farming systems around the tropics and subtropics. (Photo: ICRAF/World Agroforestry)

Figure 9.18 *Calliandra calothyrsus,* a fast-growing leguminous shrub/small tree that resprouts vigorously after pruning, is a preferred fodder species for the cut-and-carry system of silvopasture to support of animal production in smallholder farming systems. The photo shows a smallholder farmer in Kenya tending her small farm that has calliandra and other cut-and-carry fodder species planted along the farm boundary. (Photo: ICRAF/World Agroforestry)

Figure 9.19 Napier grass (*Pennisetum purpureum* syn. *Cenchrus purpureum*) behind on the right side of the stand of coconut palms as one of the components, as a cut-and-carry fodder for animals, in a coconut-based agroforestry system in Karnataka, India. (Photo: ICRAF/World Agroforestry)

major source of family income (http://www-naweb.iaea.org/nafa/news/2006-zanzibar-1.html). Similar cut-and-carry type of smallholder fodder production for stall feeding of domestic animals penned closer to the farmer's dwellings are common throughout East and Southern Africa.

9.5.2 Fodder Banks

The term refers to designated, often enclosed, areas where fodder trees and shrubs – especially leguminous ones – are grown intensively for a steady supply of fodder, especially during the dry season. The fodder available in the "banks" may be "withdrawn" and fed to cattle by cut-and-carry or by letting the animals in for controlled browsing. The main objective of fodder banks is to overcome the protein deficiency of grass that usually has low and seasonally fluctuating protein content (often going below 6%). Fodder banks should be managed to ensure high productivity and dominance of the legume as well as its persistence at the end of the growing season.

9.5.3 Boundary Planting

Boundary planting refers to planting trees as a boundary demarcation between two farms (or fields on the same farm), as a buffer between roads and farms. Live fences that are common as boundary markers between paddocks in silvopastoral systems, especially in Central American countries, consist of trees planted on property lines that serve as poles for establishing barbed-wire fence-lines. Such trees in boundary planting and live fences provide fodder, fuelwood, poles, and timber, and services like windbreaks and soil erosion control in addition to protection and privacy to the farm/plot. Moreover, by including soil-fertility-enhancing trees on boundary lines, the overall productive capacity of the soil could be improved by augmenting soil carbon input. Additional benefits will include enhanced biodiversity through various flora and fauna that the trees' environment might attract and support. This system may also be suitable for use along roadsides, watercourses, and other community amenities.

9.6 Research in Tropical Silvopastoral Systems

Research in tropical and subtropical SPS has so far been more exploratory than experimental in nature and scope. The emphasis has been on understanding and documenting the existing situation, which is the essential first step in developing research programs on any new land-use activity. The outputs of such activities are descriptions and catalogs of the systems, their characteristics, structure (nature and arrangement of components), nutritive values of the fodder from various trees and shrubs, and performance of the components and systems expressed as yield or outputs in the short term and system behavior (sustainability) in longer-terms (George et al. 1996; Mathew et al. 1992). These efforts related to tropical SPS have yielded substantial information on the nature and distribution of different types of SPS in various ecological regions, and the major tree components of each as summarized in the previous sections of this chapter. Numerous reports are available on various fodder trees that have been traditionally used, as well on relatively "new" or underexploited species (Chapter 13: Tables 13.1 and 13.2, Annexure 13-I). It was based on these efforts that certain "new" species, the potential of which had not been recognized – at least not at the current level – as fodder trees became prominent. Notable among such genera are *Leucaena, Calliandra, Gliricidia*, and *Sesbania*. Another major research accomplishment was in understanding the nutritive value of tree fodder (Chapter 11, Table 13.2). As mentioned at the beginning of Section 9.5, a new publication (August 2020) "*Alternative animal feeds from agroforestry plants,*" a special issue of the journal *Agroforestry Systems*, volume 94, issue 4 is a significant new addition to the information base on this topic.

While such efforts that focused on identifying, evaluating, and improving the fodder trees despite being resource-constrained and limited in scope have yielded some valuable information, comparable efforts on scientific approaches to improving the performance and management of these trees as components of SPS seem to have been lacking. Practically very few silvicultural or tree-improvement studies on these trees and the design of improved SPS involving them have been reported. In this context, the phenomenal success of an innovative farmer-initiated effort on rehabilitating degraded pastures in the semi-arid Caatinga region of Brazil is worth mentioning. The study evaluated the changes in the ecological (vegetation and soil) characteristics of a 24-ha smallholder farm in Barreiros, Riachão do Jacuípe (11°36’ S, 39°31’ W) in the semiarid (annual rainfall about 600 mm during 3–4 months) Caatinga region of Brazil (Pinheiro et al. 2019). The farmer’s efforts started with controlling uncontrolled grazing by free-roaming animals and then introducing several management measures including high-density planting of cactus (*Opuntia ficus-indica*), broadcasting seeds of native fodder trees, planting and nurturing tree seedlings, and managing the buffelgrass (*Pennisetum ciliare*) covers. On-farm data collected included the biomass production and water storage: stand density and species composition of shrubs/trees, soil organic carbon up to 30 cm soil depth, and percentage of soil cover on parcels of the farm that had been under 17, 10, and 3-years under SPS, as well as a degraded pasture (DP) that had been left under free-roaming grazing. Remarkable increases were recorded in the annual dry matter production (cactus+grass+trees), shrub/tree density, soil organic carbon stock, and the soil cover under the SPS systems. The interviews with the farmer indicated a possible rapid (one year) return on the investment for the SPS implementation. The study shows the enormous scope for reversing the on-going ecosystem degradation in the Caatinga, and is indicative of the high potential of such low-cost land-management interventions in the vast areas of degraded pastures in the semi-arid tropics through such innovative, farmer-designed SPS. The rapid increase in soil carbon stock makes the effort a noteworthy initiative under the concept of “4 per mille Soils for Food Security and Climate” (see Chapter 20).

9.7 Integrated Crop Livestock Forestry Systems: *New Wine in Old Bottles*?

During the past few years (since around 2010), there has been a “movement,” primarily in Brazil, to promote silvopastoral systems under a new banner “Integrated Crop Livestock Forestry Systems (ICLF).” Proposed and promoted by EMBRAPA (*Empresa Brasileira de Pesquisa Agropecuária* = Brazilian Agricultural Research Enterprise), the massive Brazilian government organization for agricultural research and development, https://www.embrapa.br, the term is different from the “Integrated Crop-Livestock Systems (ICLS)” of FAO (www.fao.org/…/spi/scpi-home/managing-ecosystems/integrated-crop-livestock-systems/) and the “good-old” agroforestry. The Embrapa website in English (https://www.embrapa.br/web/rede-ilpf/emglish) defines the term as: “Integrated crop-livestock-forest (ICLF) is an agricultural production strategy that integrates different production systems — agricultural, livestock and forestry — within the same area. It can be implemented using mixed, rotating, or succession crops, so that there is an interaction between each component, thus generating mutual benefits.” Another website, also in English states “ICLF systems are a feasible production alternative to recover altered or degraded areas. The integration of trees with pastures and/or crops is described as a system integrating the crop, livestock, and forest components, in rotation, combination, or succession, in the same area. It allows the soil to be economically exploited all year round, favoring an increase in grain, meat, and milk yield at lower costs due to the synergy created between crop and pasture.” It continues “… The above mentioned systems include the agroforestry systems (AFS), which are classified as agroforestry, forest-pasture, and agroforestry-pasture. ICLF is, therefore, the strategy with the broadest scope."

Impressive photographs of commercial land-use systems of tree plantations in zonal arrangement with crops (maize, soybean), and pasture and cattle are included on the websites; various displays and presentations on ICLF have become a feature at the international congresses and other platforms in the past few years. A book on the topic (Bungenstab and Gigolo de Almeida 2014); an international Congress in Brasilia, 2016; and publications based on ICLF in peer-reviewed research journals (e.g., Alves et al. 2017) are also available suggesting that the momentum on promoting the concept and term is on the rise. The concept is only a rehash of agroforestry. So far (January 2020) the enthusiasm in the new term seems to have been limited to some professionals in some parts of Brazil. It is too early to say if this activity is going to develop into a significant silvopastoral management option.

9.8 Outlook on Tropical Silvopastoral Systems

Silvopastoral systems in the tropics and subtropics are among the land-use activities that are at the low end of the management spectrum. These systems have received little or no attention for improvement, unlike commercial SPS in the industrialized nations. Whatever little that has been done so far has included conventional system descriptions, species inventory, and sociocultural narratives of the people and their traditions. It may sound paradoxical that despite the vast extent of areas under these systems and the large numbers of human and animal populations involved, these systems have not attracted the research and development attention they richly deserve. It is of little solace that this sort of sad state of affairs is true of all traditional low-input land-use systems.

The problems and challenges facing such systems are too many and all too familiar. Conventional, fragmented, discipline-oriented, and uncoordinated research efforts are of little relevance in tackling the issue. Strong commitment and determination, appropriate policy, and adequate resources are needed to initiate programs that cut through disciplinary barriers and perceptions, and institutional hierarchies. These may sound like lofty ideas and idealistic rantings. We can only wish that some earnest efforts are initiated at least on a pilot scale to improve these systems and demonstrate the extent of benefits that can be reaped from modest investments. After all, the land areas involved are so large, the number of hapless people who stand to benefit, and the extent of environmental and ecosystem benefits that can be reaped are so enormous that these forgotten land-use systems that offer tremendous benefits deserve the needed attention sooner than later.

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Agroforestry Systems in The Temperate Zone

10

Contents

Abstract

The temperate countries/regions considered in this chapter include the USA and Canada, Europe, southern Australia and New Zealand, parts of China, and the southern regions of South America, with the primary focus on North America and Europe where agroforestry has made significant strides. Historically, natural forests and woodlands were used for grazing in England as early as the 1600s. Similar practices were also prevalent elsewhere in Europe, Japan, and the temperate parts of India. The silvopastoral system, known as *Dehesa* in northern Spain and *Montado* in Portugal, is as old as the Roman occupation of the Iberian Peninsula. Overall, the agroforestry systems (AFS) are less diverse in the temperate zone than in the tropics in their structure (nature and

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arrangement of components) and functions (products and services). The Association for Temperate Agroforestry had recognized five AF practices in the United States: alley cropping, forest farming, silvopasture, riparian buffer, and windbreaks; urban food forestry was added as a practice in the 2010s. These practices and their variants and a few others of local relevance are also used to designate the AF practices in Europe into alley cropping or silvoarable (trees + crops), silvopasture, riparian buffer, homegardens or kitchen gradens, and forest farming. With the transformation of agriculture into market-oriented commercial farming in large, family, or corporate farms in the 20th century, the combinations of trees and arable crops became viewed opportunistically as a means to improve economic profitability. Since the turn of the century, however, interest in AFS has increased with the recognition of their ecosystem services, and support to agroforestry on farmlands is increasing. Policymakers in several countries of Europe have become appreciative of the environmental importance of silvopastoral and silvoarable systems that have been experimentally proven valuable.

10.1 Introduction

Temperate-zone agroforestry refers to agroforestry practiced in the temperate regions of the world, generally located between latitudes 30^0 and 60^0 (see Chapter 4). Throughout this zone, the climate includes distinct warm and cold seasons. Precipitation may occur throughout the year, or during either summer or winter. This seasonality engenders some unique agroforestry qualities. Unlike the tropics where the same crops may be produced throughout the year, individual crops in the temperate zone are generally restricted to one or two seasons, and fewer crops are grown each year. Extreme physiographic diversity, ranging from dry wind-swept plains to moist rainforest conditions, is another distinguishing characteristic of the zone (Section 4.5).

The USA and Canada, Europe, southern Australia and New Zealand, parts of China, and the southern regions of South America constitute the main temperate countries/regions from the agroforestry perspective; the primary focus of this chapter, however, is on the temperate zone of North America and Europe. As discussed in Chapter 4, the agroforestry systems in terms of their structure (the nature and arrangement of components: trees, crops, and animals) and functions (products and services) in the temperate zone are far less diverse than those of the tropical regions. Perhaps because of that, the agroforestry practices in the temperate zone have been grouped into fewer categories, each with more definable characteristics than in the case of tropical systems. The five distinct practices in the United States recognized by the Association for Temperate Agroforestry in the 1990s (AFTA: http://www.aftaweb.org) are alley cropping, forest farming, silvopasture, riparian buffer, and windbreaks as described in Chapter 3 (Table 3.4). Moreover, an emerging agroforestry practice called Urban Food Forests, similar to the "Urban Food Forestry" in the tropics (see Section 11.5.4) has gained considerable attention lately in North America and other temperate regions (Bukowski and Munsell 2018; Jose et al. 2020). These practices or their derivatives, along with a few others that are of local and regional relevance, are also used to identify the AF practices in Europe and other temperate regions. This chapter summarizes the experiences and advances in these five major practices. The objective is to provide practical information without details of location-specific silvicultural or agricultural and other management operations for initiating or maintaining agroforestry in existing tree plantations or new plantings; recommendations for such management operations can be obtained from local agricultural/land-management extension sources. Furthermore, the specialized and scientific aspects of issues such as the role and potential of agroforestry systems in soil management and environmental protection, climate-change mitigation, biodiversity conservation, and other ecosystem benefits are covered in the specific chapters of this book dealing with such issues.

10.2 Historical Perspectives

Historical perspectives of the development of agroforestry systems (AFS) can be traced in the temperate zone through different periods, more so in ancient cultures of Europe and Asia than in the New World. Some of the earliest records of agroforestry in Europe and the Middle East include biblical descriptions of tree-based agriculture (olives and figs), livestock in Roman olive- and orange groves (Byington 1990), and Renaissance paintings that show crop cultivation among trees and livestock being fed acorns or chestnuts from standing trees (Long 1993). Natural forests and woodlands were also commonly used for grazing, for example, with pigs in England in the early 1600s and various livestock elsewhere in Europe (Perlin 1991), Japan (Adams 1975), and India (Tejwani 1987). Reviewing the trends in the use and management of forests in Europe, von Maydell (1990) stated that encroachment into forestlands by agricultural or animal husbandry users continued until large-scale forest clearing for industrialization, which started as early as the 1500s in England (Perlin 1991). Timber production as the main objective of forest management began only about 200 years ago. Until then, the prime roles of forests, from the human perspective, were the provision of oak and beech mast acorns for wildlife (food resource for game animals), extraction of wood for fuel and construction, and grazing livestock. In some areas, such as the Mediterranean zone, northern Scandinavia, and in most mountain ranges, the use of forests for grazing is still highly important. The *Dehesa* system in southwestern Spain may be as old as the Roman occupation of the Iberian Peninsula (Joffre et al. 1988). In this land-use system, widely spaced natural oaks traditionally provided acorns for both humans and domestic animals, especially pigs, and some of the grasslands were cultivated for crops (Section 10.4.2). Similarly, native Americans often purposefully burned pine woodlands in the southeastern United States to create or maintain openings for growing crops and for promoting the growth of abundant forage material for game animals that were hunted for food (Byington 1990). Colonists from Europe brought livestock, which also grazed freely in the original pine forests in both the southern and western United States. By the 20th century, vast stretches of forest lands across the country had been cut over or converted to farms, and many of the latter were eventually abandoned to regenerate as forests or remain as range if regularly burned. Livestock grazing was common in both the cut-over land and abandoned farms.

In all of the preceding examples, the tree-based system has generally been the natural forest, frequently modified by regular burning or fruit-, nut-, or olive orchards. In the mid-1800s, farmers and other inhabitants in the plain regions in North America and Europe began to plant trees as shelterbelts and windbreaks along crop borders and around homesteads and feedlots. Although their primary function was the prevention of wind erosion, they also provided shade for grazing animals and homes, maintained a uniform snow cover, and served as a source for fuelwood, lumber, and fenceposts (Byington 1990).

Agroforestry, in one form or another, has been practiced in China since ancient times. During the Han Dynasty (206 BC–220 AD), administrators recommended the development of forests together with livestock husbandry and crops according to varying site conditions (Zhaohua et al. 1991a). Xiuling (1991) described an ancient agricultural book *Chimin Yaoshu* (Important Arts for the People's Welfare) (ca. 6th century AD), which introduced an interesting technique to grow seedlings of the Chinese scholar tree (*Sophora japonica*) and hemp (*Hibiscus* sp.) together to obtain vertical and uniform tree seedlings for planting along roadsides. He also referred to a famous book *Nongzheng Quanshu* (Complete Treatise on Agriculture) by Hsu Kunang Chi (1640) that described a kind of tree-crop mixture involving soybean between rows of Chinese chestnut (*Castanea* sp.). Another major tree-crop association described in the book is the use of shade trees in tea production (Xiuling 1991). Windbreaks and shelterbelts that have also been in existence in China for at least

400 years have since been developed into a widespread program (Section 10.5). Recent initiatives in agroforestry in China are described briefly later in this chapter (Section 10.5.4). Satoyama, the socio-ecological production landscape of Japan, is another key example of a traditional landscape management system involving croplands, woodlands, and forests (see Chapter 11, Section 11.5.8).

Socioeconomic conditions have strongly influenced land-use practices in the developed countries of the temperate zone, too, as in the tropics. Although small farms were historically dominant in the temperate zone, and still are in many regions, there has been a significant trend in the 20th century toward large, family, corporate, or communal farms, where production is concentrated on a few crops for local and distant markets. Agroforestry applications on such farms have often focused on one or two high-value crops and included high levels of mechanization. Thus, combinations of trees and agriculture used to be viewed opportunistically, i.e., to improve economic profitability. Since the turn of the century, with the increasing global recognition of the importance of agroforestry systems in environmental protection, the environmental benefits (the so-called ecosystem services) of agroforestry has become a major driving force in North America too (The major ecosystem services of agroforestry are described in detail in Sections IV and V of the book). Another significant attribute of temperate-zone agroforestry is the inclusion of numerous tree species for which a substantial knowledge base is available and market values have been established. Forestry research in this region in the past 100+ years has provided information on genetic variability, physiological characteristics, and cultural requirements for a wide variety of species, many of which have also been important in wood products markets. Management systems including agroforestry developed for and around such tree species with relatively rich scientific knowledge are different from those around the tropical multipurpose trees of unknown (or, little-known) scientific "heritage" that constitute the mainstay of tropical AFS. As in the tropical developing regions, AFS in temperate regions also have evolved during an extended period. Many systems traditionally used natural forests and woodlands in their existing condition, and livestock was generally free-grazing, although they may have been moved periodically from one area to another. Cultural activities such as burning, tree planting, or cutting have been common, but the tree and livestock components of the systems have otherwise received very little management. Only food crops associated with the systems have been subject to cultural manipulation.

10.3 Agroforestry Systems in North America

Although the level of enthusiasm in agroforestry has been increasing in the temperate regions since the late 1980s/early 1990s as described in the introductory chapters of the book (Chapters 1 and 4, especially Section 4.6), this wave may have started earlier with the publication of J. Russell Smith's classical work "*Tree Crops: A Permanent Agriculture*" (Smith 1929; reprinted: Smith 1950). Based on his travel experience and observations of the Mediterranean agriculture, Smith argued that "an agricultural economy based almost entirely upon annual crops such as corn and wheat is wasteful, destructive of soil fertility, and illogical," and advocated North American agricultural systems using nut trees (such as *Carya* spp., *Juglans* spp., oaks (*Quercus* spp.), persimmon (*Diospyros* spp.), and honeylocust (*Gleditsia triacanthos*). Following the Great Depression of the 1930s, work on tree crops commenced especially in the eastern US under the auspices of the Tennessee Valley Authority (TVA), concentrating on black walnut (*Juglans nigra*), Chinese chestnut (*Castanea mollisima*), filbert (*Corylus* spp.), hickories, persimmon, and honeylocust. Unfortunately, the tree crops idea was almost forgotten in the 1950s and 1960s during the post-war economic boom. The 1970s saw a renewed interest in tree crops because of the energy crisis. The mounting concerns about the high rate of agrochemical and energy use in industrialized agriculture and the realization of the adverse effects of soil erosion in row-crop agriculture led to the development of awareness regarding the potential role of trees as an effective component in the overall solution to these problems (Gold and Hanover 1987). It was, however, since the late 1980s that the momentum on temperate agroforestry was built up with the initiation of the series of North American Conferences of Agroforestry, which has been held once every two years since 1989, and the establishment in 1991 of the AFTA.

Numerous publications and data sources are available on the various agroforestry research and development initiatives in different parts of North America; the AFTA website (http://www.aftaweb.org) is a good starting point for accessing them. Gold (2019) summarized 35 years of developments in the subject. Multiple editions of a comprehensive book *North American Agroforestry: An Integrated Science and Practice:* [second edition (Garrett (2009); third edition (Jose et al. 2020)] are excellent reference sources. Two editions of the book titled *Temperate Agroforestry Systems* (Gordon and Newman 1997; Gordon et al. 2018) provide broad perspectives on temperate agroforestry. A national assessment report on agroforestry by the USDA (US Department of Agriculture) Forest Service (Schoeneberger et al. 2017) provided a science-based assessment of the benefits that agroforestry can confer and a framework for including agroforestry systems in agricultural strategies to improve productivity and food security and build resilience in landscapes. It presents a comprehensive North American perspective on the strengths and limitations of agroforestry by way of US regional overviews as well as overviews for Canada and Mexico and includes a range of national stakeholder perspectives with participation from a wide range of public, private, and non-governmental entities, academic institutions, and professional organizations. The key areas of agroforestry opportunities in the mainland USA gleaned from the regional summaries included in that report are summarized in Table 10.1. Bentrup et al. (2018) of the USDA, and Lovell and Garrett (2021) of the University of Missouri Center for Agroforestry, have published annotated bibliographies on the status of Agroforestry in North America that has brought together almost all the relevant publications on the topic.

As in the rest of the world, robust statistics are not available about the area under agroforestry in North America; but area statistics are estimated based on other relevant records. Jose et al. (2012) estimated the potential land area available for agroforestry in the USA as 143.6 million ha (Table 10.2). Sharrow et al. (2009) estimated the area currently under silvopasture in the US as 13% of all grazing lands in the country or 54 million ha, whereas Jose et al. (2012) reported the area potentially available for silvopasture as 77.7 million ha.

10.3.1 Alley Cropping

At the outset, it needs to be clarified that the reference here is to Temperate Alley Cropping (that is different from Tropical Alley Cropping, described in Chapter 6). Conceptually, the main difference between the two forms is that in the tropical version, a major emphasis is placed on using tree foliage as a source of nutrients for crops or/and as animal feed, whereas in the temperate zone, there is no such emphasis or intention on using the tree foliage as a source of nutrients for crops or for restoring soil fertility. Based on this, and also in consideration of the use of farm machinery, which is an essential aspect of farming in industrialized countries unlike in the tropics, there are clear differences between tropical and temperate alley cropping in all aspects of tree management, including species selection, spacing, planting configurations, and pruning. Whereas tropical alley cropping is essentially a form of hedgerow-intercropping primarily of fast-growing leguminous trees and shrubs, temperate alley cropping involves planting rows of crops between widely-spaced rows of tree species of high economic value such as timber- and fruit-/nut-producers (Figures 10.1, 10.2, and 10.3).

In the Midwestern United States and parts of Canada such as Ontario, high-value hardwoods are the tree species used mostly in alley cropping, black walnut (*Juglans nigra*) being the most common (Figure 10.1). The desirable growth and shade characteristics, wood quality, and high market value of its timber and nuts make black

Table 10.1 Agroforestry opportunities in the different regions of mainland USA[1]

Region and its predominant land use	**Climatic challenges** faced by farmers and ranchers	**Agroforestry options** to address the challenges
Northwest One-fourth of the region's land area is agricultural; provides 52, 17, and 11 percentages of the nation's potato crop, wheat, and milk, respectively. The region's tribal communities have traditionally practiced agroforestry.	Heat stress, decreased chilling hours, increased drought, and reduced snowmelt.	Silvopasture, windbreaks, and alley cropping may offer potential for modifying microclimate. Riparian buffers may lower stream temperature to protect salmon and such other cold-water species.
Southwest Producer of more than half of the country's specialty crops (fruits, nuts, and others) that are irrigation-dependant. Extensive rangelands for livestock and dairy production,	The already parched region is expected to get hotter and drier, especially in the southern half including California.	Silvopastoral systems may reduce fuel loads and the severity of forest fires. Increased irrigation may enhance nut- and fruit production of AF trees.
Great Plains Croplands, pasture, and rangeland occupy more than 80% of the land area; total market value is about equal between crop and livestock production,.	Known for historical weather extremes; climate change may cause hotter temperatures, heavier rain and snow events, and intense droughts.	Windbreaks have a long tradition of combating impacts of adverse climate since the 1930s' Dust Bowl; riparian buffers are improve water quality and streambank stability.
Midwest More than two-thirds of the land area is under agriculture, corn and soybean being the major crops.	Alternating flood and drought cycles, and high incidence of pests are two major climate-change-related problems.	Riparian buffers for water-quality enhancement and soil conservation; windbreaks and alley cropping for buffering temperature.
Northeast About 21% of the land area is under agriculture, primarily for dairy and poultry production.	Increasing heat waves and extreme precipitation events causing floods	Silvopasture for moderating heat stress on animals; forest farming for reducing the conversion of forest cover to other forms of land use.
Southeast The diverse region produces major shares of broiler chicken, peanuts, cotton, and tomatoes in the U.S.	Common problems include extreme heat in summer, sea-level rise, declining fresh water availability, and algal blooms of coastal areas	Silvoasture, alley cropping, forest farming, riparian buffer.

[1]Source: Adapted from Schoeneberger et al. (2017)

Table 10.2 Potential land area available for the five categories of agroforestry practices in the United States

Practice	Predominant Region (s)	Use(s)	Associated Technologies	Potential Area[1] (million ha)
Riparian and upland buffers	All Regions	Ameliorate nonpoint source pollution Abate soil erosion and nutrient loading, Protect watersheds Modify microenvironments and protect aquatic habitats Create wildlife corridor	Streambank bioengineering Constructed wetlands	1.69
Windbreaks	Great Plains	Protect and enhance production of crops and animals, control soil erosion, distribute snowfall. Trap snow.	Living snow fences	8.95
Alley cropping	Midwest	Increases and diversifies farm crops and income, creates wildlife habitat	Plantation management	17.9
Silvopasture	All Regions	Economic diversification, improve animal health, fire protection, timber management	Pine straw harvest	77.7
Forest farming	All Regions	Income diversification	Forest management	37.35

[1]Source: Udawatta and Jose (2011)

Figure 10.1 Alley cropping with black walnut (*Juglans nigra*) and orchard grass (*Dactylis glomerata*), Missouri, USA. (Source: USDA National Agroforestry Center)

Figure 10.2 Chinese chestnut (*Castanea mollissima*) + wheat alley cropping system in Missouri, USA. (Photo: BM Kumar)

walnut the most valuable tree species in North America in plantations as well as alley cropping (Garrett and Harper 1999; Garrett et al. 2009). With the foliage (growth) period about 135 days a year, the tree is one of the last species to put out leaves in the spring, which allows additional days of full sunlight to intercropped species such as winter wheat and barley (*Hordeum vulgare*) that mature in the spring. It is also one of the first trees to defoliate in the fall (autumn), which allows the availability of sunlight for longer periods for warm-season intercrops. The black walnut, however, is a species that has the attribute of allelopathy (production of chemicals that inhibit the growth of companion crops), that sets limitations on its suitability for intercropping; juglone, the allelochemical produced by the plant, causes some restrictions on the growth of understory

Figure 10.3 Alley cropping: pecan trees (Carya illinoinensis) + cotton (*Gossypium* sp.), Southwestern Florida, USA. (Source: USDA National Agroforestry Center)

species. The problem, however, can be addressed by proper management methods such as the selection of appropriate companion (understory) species, planting arrangement, etc. (Jose and Holzmueller 2007; Jose et al. 2012).

Pecan (*Carya illinoensis*) is another tree that produces both nuts and wood and is widely used for alley cropping throughout the southern United States. Although it produces denser foliage than black walnut, it allows light transmission that is adequate to support understory species (Figure 10.3). Chestnut (*Castanea* sp.) is a potentially good nut-bearing species for alley cropping. American chestnut (*C. dentata*) that used to be popular throughout the eastern USA has, unfortunately, been eliminated by the chestnut blight (*Endothia parasitica*), but blight-resistant Chinese (*C. mollissima*) and Japanese (*C. crenata*) chestnuts and American hybrids are available (Gold 2019; Jose 2019) for alley cropping. Honey locust (*Gleditsia triacanthos),* ashes (*Fraxinia* spp.), oaks (*Quercus* spp.), and basswood (*Tilia* spp.) are some of the conventional hardwood species suitable for alley cropping (Garrett et al. 2009). Nitrogen-fixing trees (NFTs) that are quite valuable for alley cropping in the tropics are not popular in temperate North America; however, some members of tropical NFT genera such as *Albizia*, *Lupinus*, *Prosopis* (mesquite), and *Robinia* offer opportunities for use in warmer southwestern parts of North America.

Poplar species (*Populus* spp.) and their hybrids constitute one of the most widely intercropped groups of trees and they have traditionally been planted for short rotation fiber and fuel production. Poplar plantations in Europe and eastern Canada have been interplanted with several crops including corn, potatoes, soybeans, and other cereal and tuber crops, in different temporal sequences, for the first three to six years after tree establishment (Gold and Hanover 1987; Thevathasan et al. 2012). Poplar is also frequently interplanted with several other crops in subtropical northern India (see Figures 12.5, 12.6, and 12.7 in Chapter 12) and Pakistan. Many of the poplar plantations are intercropped with agricultural crops, especially during the early stages of tree plantations; the trees are then allowed to grow for five to 10 years in sole stands (without intercropping) and then harvested, and the next rotation established. Among the exotic tree species, *Paulownia tomentosa,* a native of central and western China with high-value wood and fast growth that is commonly intercropped in China (see Section 10.5.3), is a potentially valuable species for intercropping in the eastern USA and is promoted by the American Paulownia Association (https://paulowniatrees.org). Alley cropping with various hardwood species as well as understory species (including grapevine: *Vitis vinifera;* Figure 10.16) is practiced, also in other temperate regions of the world as mentioned later (see Section 10.5).

10.3.2 Silvopastoral Systems

The practice of livestock grazing in plantations, especially conifer plantations, has been more widely utilized and reviewed than any other agroforestry system in the temperate zone. The approach varies from the relatively simple management system in which livestock are allowed to graze freely in plantations established essentially for timber production, to situations in which trees and pastures are purposely managed to accommodate a long period of carefully controlled livestock production. Although the system occurs in many developed countries, it is most common in North America, Australia, and New Zealand.

In the United States, examples of grazing in plantations include cattle grazing in industrial pine plantations in the southeast, and sheep grazing in Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) forests in the northwest. In both regions, the primary forage species are natural grasses, herbs, and shrubs. Moreover, grazing in managed natural forests and mixed hardwood forests in the northeastern and midwestern US is a practice that is becoming increasingly popular (Orefice et al. 2017; Ford et al. 2017; Stewart et al. 2020). The livestock is generally, but not necessarily, excluded from the plantations during the early years of tree establishment because of possible damage to seedlings. Even in these early years, livestock may be allowed to graze during seasons when the non-conifer vegetation is more palatable than the seedlings. As the seedlings grow above the height of livestock, the practice becomes more common and less restrictive in terms of animal management. Livestock is moved to lower elevations in the winter. In many plantations, the animals are used as a method of biological control for vegetation that would normally compete with seedlings. Similar systems of livestock grazing management are also common during the summer in the forested mountains of western Canada. In some of these systems, native forages have been improved by prescribed burning, fertilization, or seeding of grass and legumes (Byington 1990; Thevathasan et al. 2012).

The vast majority of research on silvopastoral systems in North America has focused on pine forests with deliberate management of both pasture and trees (Figure 10.4 and 10.5); however, silvopasture under hardwood species is also common (Figure 10.5). These systems are most

Figure 10.4 Silvopasture with pines in Florida. (Source: IFAS, University of Florida)

Figure 10.5 Silvopasture with hardwood species in North America. (Source: USDA National Agroforestry Center)

important in the Southern Coastal Plain under slash pine (*Pinus elliottii*), and longleaf pine (*Pinus palustris*); they are popularly known as "pine-and-pasture" or "cattle-under-pine" systems. The earliest studies on pasture improvement in these systems, initiated in the 1940s, indicated that mechanical site preparation and fertilization were essential for forage establishment, and that production of established pasture declined with increasing tree-canopy closure (Lewis and Pearson 1987). Among the most productive pasture species were Pensacola bahiagrass (*Paspalum notatum*), annual lespedeza (*Lespedeza striata*), and white clover (*Trifolium repens*), with Pensacola bahiagrass being the most shade tolerant.

In the 1950s, a study introducing cattle into pine/pasture mixtures was initiated to compare tree growth with differences in tree spacing, grass species, and fertilization (Lewis and Pearson 1987). Slash pine seedlings were planted at 3.7 X 3.7 m and 6.1 X 6.1 m spacing, and allowed three years of growth before the introduction of Pensacola bahiagrass, coastal bermuda grass (*Cynodon dactylon*), or dallisgrass (*Paspalum dilatatum*). Control plots of uncultivated, unfertilized pine/grass mixtures, in addition to native pastures, were also maintained. Cattle were introduced in the fifth year for annual grazing. The twenty-year results showed that the trees were larger in the fertilized plots; the wider spacing (6.1 x 6.1 m) increased tree diameter and cattle weight gains, but not wood yields; bahiagrass again proved to be the most shade-tolerant and high-yielding forage species. Various tree densities and planting arrangements were also tested as a part of the project. The standard tree-density and arrangement were approximately 1110 trees ha^{-1} at 2.4 x 3.7 m spacing. For silvopastoral management, the best arrangement was shown to be a double-row configuration of (1.2 x 2.4) x 12.2 m (or (4 x 8) x 40 feet) in terms of both forage production and wood production at mid-rotation (Lewis and Pearson 1987). Based on subsequent monitoring of these plots, Sequeira and Gholz (1991) reported that although light penetration and soil temperature were higher in the double-row stands, crown development and stem volumes of trees up to age 18 were superior in single-row stands. The authors suggested that there was great potential for optimizing both tree growth and understory microclimate by joint manipulation of crown structure and stand configuration in silvopastoral systems.

Injury to or mortality of pine seedlings, poor quality of forage, and production of low-quality timber are the major constraints of this system. Delayed introduction of cattle, coupled with controlled stocking rates and improved forage grasses and legumes, are suggested as solutions to the first two problems. Pearson's (1983) analysis of twenty-year research data showed that multiple-use benefits of tree and cattle production and increased flexibility in land management could provide sufficient economic gain to offset the timber-quality problem. Based on sensitivity analyses using various discount rates, Dangerfield and Harwell (1990) also reported that a mixed land-use practice combining trees and grazing in the southeastern United States provided favorable cashflow to the land user, and mitigated the negative cashflow periods associated with conventional forestry production.

In general, grazing in plantations with normal spacing for timber production becomes less feasible as trees begin to shade out forage vegetation 5 to 15 years after establishment. Forage production and grazing periods can, however, be extended by either substantially increasing tree spacing and/or altering planting configurations. Although the technical feasibility of altering planting configuration to sustain forage production without reducing timber yield has been adequately demonstrated, the practice has not been widely implemented. The prevailing attitudes of traditional user groups could be one of the major factors that hinder the large-scale adoption of the practice. For example, livestock damage to young pine trees and the manipulation of forest structure for grazing may be viewed unfavorably by many foresters, landowners, and other natural resource managers who have focused primarily on timber production. On the other hand, traditional livestock producers contend that grazing provides indirect benefits to timber production on forestland, but are often unwilling to place trees on their pastures.

Increased adoption will probably occur only as private landowners see others purposefully combining pasture, cattle, and timber production (and gaining economic benefits from the system). Based on a review of the silvopastoral systems in North America, Sharrow et al. (2009) concluded that “although it is unlikely that they (silvopastoral systems) will experience explosive growth in the next decade, they have a bright future and will find a place in modern agriculture.” The experience of the past decade (2010–2019) shows the above prediction to be true by and large, and the fact remains that silvopasture is the most widely practiced AFS in North America. A literature review by Jose et al. (2019) concluded that silvopastoral systems have greater biodiversity and multifunctionality compared with other livestock-production methods. However, their complex functional dynamics make it comparatively more difficult to manage them; therefore, optimization of temporal and spatial resources, maximization of positive interactions, and minimization of negative interactions are critical for the successful management of silvopastoral systems.

10.3.3 Windbreak Practices

Windbreaks and shelterbelts are barriers used to reduce wind speed (Brandle et al. 2009). The practice of establishing windbreaks by planting rows of trees at right angles to the prevailing wind direction is more than a century-old in North America’s Great Plains. The early settlers from Europe, who were not comfortable with the unending treeless plains, planted trees around their farmsteads, hoping to break up the monotony of flat plains as well as provide protection from constant winds. In 1935, at the peak of the Great Depression, US President Franklin Roosevelt established the Prairie States Forestry Project with the hope of decreasing the wind erosion of topsoil by planting trees around agricultural fields from North Dakota to Texas. Initially, the term “Shelterbelt” was defined as “tree planting designed to protect fields from soil erosion caused by wind and to increase crop yield” and “Windbreak” as tree planting designed to provide wind protection for a farmstead or a feedlot (Baer 1989). These differences have gradually disappeared and the terms are currently used rather interchangeably. The species so planted usually consist of trees and shrubs, but perennial and annual grasses and crops and fences made of wood and other materials are also used. Windbreaks are deliberately planted and maintained to protect crops and livestock from wind hazards, offer habitat for wildlife, provide tree products, and improve the overall landscape aesthetics (Figure 10.6). A windbreak (on the

Figure 10.6 Windbreaks in North Dakota, USA. Some of the common tree species used include green ash (*Fraxinus pennsylvanica*), common hackberry (*Celtis occidentalis*), Siberian elm (*Ulmus pumila*), and basswood (*Tilia americana*). (Source: USDA National Agroforestry Center)

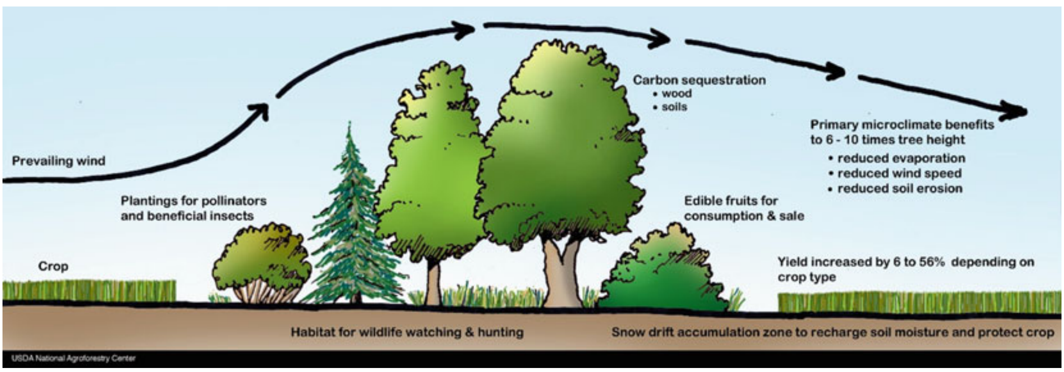

Figure 10.7 A schematic presentation of the effects of multifunctional windbreaks. (Source: USDA National Agroforestry Center)

land surface) obstructs the wind flow and alters flow patterns both the windward and leeward; windward refers to upwind of the barrier, the direction from which the wind is coming and approaching as it hits the barrier, and leeward refers to downwind of the barrier, or the direction to which the wind leaves. A schematic presentation of the effects of multifunctional windbreaks proposed by the USDA National Agroforestry Center is presented in Figure 10.7.

As in the tropics, wind erosion is a serious problem in many parts of the temperate zone, and the use of windbreaks to protect agricultural fields and homesteads is a common agroforestry practice in those areas. The greatest benefits from the use of windbreaks in the temperate regions occur in areas with winter snow and hot, dry, windy summers as in the Great Plains of the midwestern United States, Russia, and China (Byington 1990). The "Green Great Wall" program of China, launched in 1978, is perhaps the longest windbreak/shelterbelt project in the world. Not to be confused with "The Great Green Wall of Africa, a similar anti-desertification effort in Africa (Chapter 18, Figure 18.10), the Chinese program is formally called "The Three-North Shelter Forest Program," also known as the Three-North Shelterbelt Program, Green Great

Wall, or Great Green Wall. Based on reports in popular newsmedia such as the BBC, *The Guardian*, and CNN, and publications such as *National Geographic*, it includes a series of human-planted windbreak strips (shelterbelts), designed to hold back the expansion of the Gobi Desert. The Gobi Desert reportedly (Wikipedia) overtakes 3,600 km^2 of grassland every year; its dust storms blow off as much as 2,000 km^2 of topsoil every year with increasing severity and is a major threat to agriculture not only in China but neighboring countries of Japan, North Korea, and South Korea as well. The Green Great Wall program started in 1978, and the 4,500 km (2,800 mi)-long program is planned to be completed around 2050. The broader objectives of the program include rehabilitation of wasteland, development of vegetation for the control of sandstorms, and control of soil and water erosion through large-scale afforestation and grassland development. During the first phase (1978–1985), 6.7 million ha of farmland and 3.4 million ha of pastures have been protected through farmland shelterbelts, dune-fixing forests, and other tree-planting activities (Zhaohua et al. 1991b).

Under normal arid conditions of the US Great Plains, windbreaks modify the microclimate of the protected zone by decreasing wind velocity. Consequently, vertical transport of heat is reduced and humidity is increased behind a windbreak, which generally reduces evapotranspiration. Furthermore, during periods of water stress, stomatal resistances are lower in crops protected by windbreaks than in crops grown in the open. Lower stomatal resistance tends to result in increased photosynthetic rates in the protected area. During the summer, the warmer day temperatures may increase evaporation from plants, but during early spring they may be beneficial for the establishment of most crops (Brandle et al. 2009). Another microclimatic influence of the windbreaks is the conservation of or increase in soil moisture due to more evenly distributed snow and, thus, snowmelt in the spring. These beneficial effects can result in increased crop production in areas protected by windbreaks.

Windbreaks also have positive impacts on livestock production, mainly by livestock protection from hot winds and dust during summer and cold winds during winter. Lower wind velocities reduce the effect of wind chill in cold weather, and the extent of energy animals need to maintain body temperatures, which, in turn, can reduce feed costs and improve animal production. As with other types of windbreaks, livestock windbreak needs to be designed for each specific operation (Brandle et al. 2009). Another application of windbreaks and shelterbelts in agriculture is their use for odor mitigation (Tyndall and Colletti 2007). Shelterbelts located in/around livestock research facilities can play an important role in biophysically and sociopsychologically mitigating odor in an economically feasible way, and the opportunities are increasingly attracting the attention of poultry, swine, and dairy operations in North America (Jose et al. 2012).

The magnitude of wind speed reduction at locations within the zone protected by the windbreak is a function of windbreak structure. Zhou et al. (2008) pointed out that the ability of a windbreak to reduce the wind speed is a function of its external structural features (such as height, orientation, length, width, and continuity or uniformity) and internal structural features (the amount and arrangement of the solid and open portions and the surface area of the barrier components that contribute to the overall porosity of the barrier). In general, a denser windbreak is less porous and offers more reduction of wind speed: narrow windbreaks composed of three to four rows of trees planted at moderate density, and positioned at an angle as close as possible to 90^o to the predominant wind direction are the most efficient. In areas where wind direction changes frequently, it is common to plant windbreaks perpendicular to one another.

The distance between windbreaks is another major factor to be considered in windbreak design. If the height of the windbreak is H, generally, its protective influence extends to areas of up to 20 H distance. Multiple factors, such as soil characteristics, crop response to protection, and the area of cropland that is lost to windbreaks, can affect the spacing between windbreak lines. On fairly stable soils and for moderately responsive crops such as cereals, the commonly-adopted distance between windbreaks is 15–25 H (Byington 1990). For forage crops, spacings of 10–14 H may be justified if the additional yield is sufficient to balance the losses from the reduced crop production area. The spacing could be profitably decreased even further in highly erosive soils.

Windbreak efficiency also is affected by the type of trees and shrubs planted. Species that can survive and grow in difficult and diverse conditions, while providing needed structure and protection are preferred. Dense crowns, stout boles, retention of lower limbs, and uniform rates of growth are all characteristics conducive to creating effective windbreaks (Byington 1990). Fast-growing species are desirable for quick establishment and height increment. While some broadleaved species grow faster than conifers, they are usually deciduous; in contrast, conifers are long-lived and, since they retain their foliage, maintain the same density year-round. Often, for best results, both conifers and broad-leaved species are grown together in windbreaks. The most commonly used windbreak species in North America include silver maple (*Acer saccharinum*), saltbush (*Atriplex canescens*), hackberries (*Celtis* spp.), Russian olives (*Elaeagnus* spp.), ash (*Fraxinus* spp.), honey locust, black walnut, juniper (*Juniperus* spp.), spruce (*Picea* spp.), pines, sycamore (*Platanus occidentalis*), poplar, Douglas-fir, and bur oak (*Quercus macrocarpa*) (Brandle et al. 2009).

The benefits of windbreaks for agriculture in the temperate zone have long been recognized; consequently, institutions in the US, Canada, Europe, Australia, New Zealand, and China are currently involved in windbreak research. Tree improvement and pest management of windbreaks have perhaps received the most research attention. Other research priorities in the past included windbreak establishment and management, analysis of benefits and costs, and quantification of biophysical windbreak effects (Brandle et al. 2009). Despite these efforts, significant problems remain: windbreak establishment continues to be difficult; there is a very limited choice of medium-to-tall species that are well-adapted and long-lived; better methods are needed for weed control, pest management, and silviculture of the windbreaks; improved understanding of the effects of windbreaks on agricultural crops, especially the benefits and costs of the practice, is necessary; and windbreak design for the hilly country is currently inadequate. Despite a long history of windbreaks in land-use systems, major research opportunities remain untapped for this important agroforestry practice.

10.3.4 Riparian and Upland Buffers

Buffers, in this context, refer to “strips of perennial vegetation (tree/shrubs/grasses) planted between croplands/pastures and streams, lakes, wetlands, ponds, etc.” (Figures 10.8 and 10.9). Riparian areas, however, are defined in several ways. After reviewing the various definitions including those proposed by US government agencies such as USDA and the Bureau of Land Management, Schultz et al. (2009) stated that the common threads among the various definitions are that a riparian area is adjacent to a body of water, has no clearly defined boundaries, and is a transition zone between aquatic and upland environments. A riparian forest buffer is “an area of trees, usually accompanied by shrubs and other vegetation, that is adjacent to a body of water . . .” (Palone and Todd 1997). In agricultural landscapes, buffers serve to reduce losses of soil and nutrients that typically remain within an ecosystem of undisturbed or perennial vegetation. These buffers are established at the edges of “leaky” ecosystems adjacent to the riparian area to reduce the impact of upland sources of pollution. In the relatively more humid parts of the eastern and midwestern United States, they typically exist as continuous narrow bands or irregular patches of remnant forests along meandering streams. The main purpose of upland buffer practices is to reduce nonpoint-source pollution from agricultural watersheds and to improve water quality (Schultz et al. 2009; Udawatta et al. 2011). In Northwest USA, riparian buffers

Figure 10.8 A riparian buffer,13 years after establishment, at the Bear Creek watershed in Iowa, USA. It includes mixed hardwood trees, shrub species and a native prairie mix of about 15 different grass and forb species. (Photo: Iowa State University NREM Buffer Team)

Figure 10.9 Another view of a Riparian Buffer. (Source: USDA National Agroforestry Center)

may serve to lower stream temperatures (shade for the water body) to protect salmon and other cold-water species of fish while in the Midwest they serve to enhance water quality and for soil conservation (Table 10.3).

The design of upland buffers will have a major influence on their efficiency in reducing nonpoint-source pollution from agricultural watersheds. Soil type, slope, precipitation, and management are the main factors to be considered. Sediment removal efficiencies in different soil types will usually be in the order: sand < sandy loam < silt < silt clay loam < silt loam. Site-specific characteristics of the surface and subsurface horizons also need to be considered. In general, contour buffers and grass barriers should be along (parallel to) the contour lines as closely as possible. Filter strips are typically the widest (> 5m) among the different buffer strips and are established between field borders and waterways (Blanco-Canqui et al. 2004).

The upland buffers could be either grass only or a combination of grass, shrubs, and trees (Figure 10.10). Tree species that are commonly recommended for planting in the US Midwest include species of willows (*Salix* spp.), elder (*Sambucus* spp.), birch (*Betula* spp.), maple (*Acer* spp.), and ash (*Fraxinia* spp.). Sycamore

Table 10.3 Percentage reduction of sediment, total nitrogen, and total phosphorus losses on grazing and row crop management practices with agroforestry and grass buffers compared to the respective control treatment

Parameter	Managements and Treatments			
	Grazing Management		Row crop Management	
	Agroforestry	Grass buffer	Agroforestry	Contour Grass
	---------------------------------- % ----------------------------------			
Sediment	48	23	30	28
Total nitrogen	75	68	11	13
Total phosphorus	70	67	26	22

Source: Udawatta et al. (2011)

Figure 10.10 An upland buffer with trees and grasses at the Greenley Memorial Research Center of the University of Missouri. (Photo: Ranjith Udawatta, The Center for Agroforestry, University of Missouri)

(*Platanus occidentalis*) and different species of oaks (*Quercus rubra*, *Q. alba, Q. palustris, Q. bicolor*) are also used, but they are less tolerant of flooding. Common warm-season grasses for buffer strips include switchgrass (*Panicum virgatum*), gammagrass (*Tripsacum dactyloides*), purple coneflower (*Echinacea purpurea*), big bluestem (*Andropogon gerardii*), and others. Various other locally available tree-, shrub-, and grass species are also commonly used. Udawatta et al. (2002) working on three adjacent watersheds in northeast Missouri involving contour planting of 3- to 4-m-wide buffers at 22 to 36 m spacing showed that tree + grass and grass buffers removed significant amounts of sediments and nutrients from runoff. A recent meta-analysis by Lind et al. (2019), including publications from different countries since 1984, concluded that drainage size (i.e., the width of the strip) mattered for nutrient and sediment removal and that a 3-m wide buffer strip could act as a basic nutrient filter. A summary of buffer width of the riparian zone needed for reduction of nitrogen (N), phosphorus (P), and sediment removal proposed by the authors based on their analysis is given in Figure 10.11. The authors also developed the concept of an "Ecologically Functional Riparian Zone" based on a proper balance between agricultural needs and environmental protection.

The choice of vegetation types and species within the riparian buffer is also of great significance. For example, if nutrient leaching is of concern in sandy soils, it might be prudent to consider deep-rooted trees to remove the nutrients

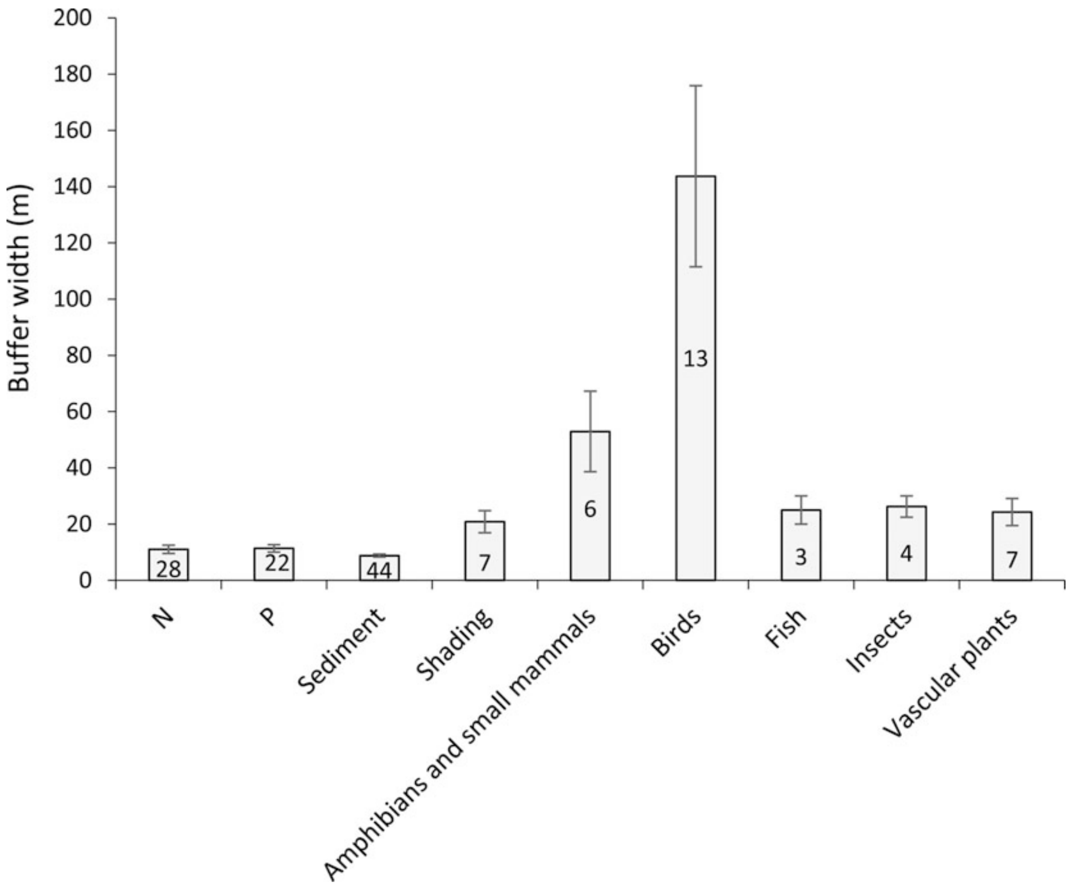

Figure 10.11 The width of the riparian zone needed to fulfill different ecosystem services for reduction in nitrogen (N), phosphorus (P) and sediment inputs ($\geq$75% removal efficiency), shading, and protecting/promoting biodiversity and plants and animals. The figure is based on quantitatively derived width recommendations from 134 data points from 43 peer-reviewed studies. Number of data points for each ecosystem function are indicated in the different bars. Data are means $\pm$ 1 SE.
Source: Lind et al. (2019).

(Nair et al. 2007). Grasses will likely remove nutrients from the surface of the soil, and their roots will strengthen and stabilize stream banks; they may, however, have minimal effect in removing nutrients deeper in the soil profile. Grasses could intercept surface runoff and filter sediments. Furthermore, trees and shrubs could create shade and increase biodiversity; they could provide a habitat for terrestrial and aquatic plants and animals.

Opportunities for integrating ornamental woody plants and nut- and fruit-producing trees to enhance aesthetics, support wildlife, and earn additional income, are promising (Gold et al. 2004), and the environmental benefits from riparian buffers have been scientifically well established. However, the acceptance rate by the farming community has been rather slow. The primary reason, which is common to other agroforestry practices such as alley cropping too (Section 10.3.1), is the well-known conservation *versus* production dilemma, i.e., reluctance to committing valuable land to an unfamiliar management system that may not provide any direct and immediate benefit (Schultz et al. 2009; Trozzo et al. 2014). Landowners are also concerned that government incentives such as the Conservation Reserve Program by which they are attracted to the new practices may be short-lived, and once the program ends, they may have to reclaim the land by removing the buffers including trees that could turn out to be expensive. With proper extension and government support programs, farmers could, however, be more willing to adopt native fruit-and-nut-tree agroforestry riparian buffers to achieve both conservation and production.

10.3.5 Forest Farming

As an agroforestry practice, Forest Farming involves the cultivation or management of understory crops within an established or developing forest (USDA National Agroforestry Center 2007; Chamberlain et al. 2009). To some extent, it originates from the traditional and informal farming in the forest that has been practiced for generations all over the world. Agroforestry Forest Farming represents integrated management of timber and non-timber forest crops with emphasis on specialty crops and non-timber forest products (NTFP) for diversifying and stabilizing income sources, increasing forest health, and promoting alternative "green" enterprises. Examples of NTFP include food and food additives (edible nuts, mushrooms, fruits, herbs, spices, condiments, aromatic plants, game), fibers (used in construction, furniture, clothing, or utensils), resins and gums, and plant and animal products used for medicinal, cosmetic, or cultural purposes (Figures 10.12 and 10.13). The array of products, outputs, and services derived from the forest is so large and diverse that all forest framing practices involving such components and management operations may not sometimes be considered as agroforestry *sensu stricto*. Indeed, considering that agroforestry is a concept that cannot be confined within the bounds of a strict definition and the progress in agroforestry has not been hampered by the lack of a universally accepted definition (Chapter 2), a discussion on whether all forest farming practices come under agroforestry is a rather moot point. Plants commonly farmed in North American forests (Table 10.4) are relatively few compared with the tropical situation. Most forest farming activities involving such plants constitute the so-called recreational- or hobby farming, guided more by traditions and experience rather than the directives and recommendations of public or private research entities or the motivation for yield- and profit maximization.

Figure 10.12 Forest Farming. Ginseng (*Panax quinquefolius*) and other botanicals as the understory of trees on the farm of forest farmer Dave Carman in Princeton, West Virginia, USA. (Photo: Catherine Bukowski of www.communityfoodforests.com)

Figure 10.13 Forest farming: Cultivating Shiitake mushroom, *Lentinula edodes,* on forest logs. Source: Wellspring Forest Farm, Mecklenburg, New York

Table 10.4 Some common medicinal and culinary plants farmed commercially in forests of North America

Common Name	Scientific Name	Description	Product/Use	Region
Black Cohosh	*Actaea racemosa*	Herb; delicate, lacy-type foliage	Roots: treatment of menopausal symptoms	Throughout
False Unicorn (Star root)	*Chamaelirium luteum*	Herb; separate male and female plants	Woman's herb	Throughout
Gingko	*Gingko biloba*	Ancient tree, ornamental; grown in monocultural plantations	Leaves used to enhance memory and treat circulatory problems	Throughout
Ginseng	*Panax quinquefolium* (American Ginseng); *P. ginseng* (Asian Ginseng)	Herb; seed-propagated; difficult to grow	Roots; Used as general tonic, aphrodisiac.	Eastern US and Canada
Godenseal	*Hydrastis canadensis*	Perennial herb with thick yellow knotted rootstock.	Roots; medicinal: for treating open cuts and wounds, heart disorders.	Eastern US and Canada
Mushrooms	The most popular is Shiitake: *Lentinula edodus*	Grow best on hardwood logs cut from live trees		Moderate, moist climate, 18 – 24 ^{0}C.
Syrup: Sugar maple	*Acer saccharum*	Grows in mixed hardwood forests		Eastern US and Canada

Forest farming represents a form of agroforestry that is different from most other agroforestry practices. While the underlying strategy of almost all agroforestry activities has been based on the concept of trees in support of agriculture, forest farming involves the introduction and management of other species, usually herbaceous and native, within existing forests. Sholto and Hart (1985) are often credited for recognizing that farm forests were ecosystems in themselves, and proposing that forest farms be designed to conform to ecological principles and practices. But J. Russell Smith (Section 10.3) proposed in 1929 the "progressive establishment of massive complexes of tree farms" and he envisioned "hills green with crop-yielding trees" (Smith 1929). The fundamental purpose of forest farming as suggested by Sholto and Hart (1985) is to integrate the components into a complete stable dynamic system, the components of which support the productive function of the others. As Chamberlain et al. (2009) emphasize, forest farming has advantages and disadvantages, and landowners need to be aware of them. While well-designed and well-implemented forest farming can improve forest health and provide additional income, farmers may have to face the inadequacy of the information base on the management of different components of the farm and the marketing structures. Although this applies to agroforestry in general, multispecies and multicomponent forest farming on a commercial scale could pose an overwhelming challenge for the less tenacious and entrepreneurial landowners.

Specialty Crops. This term is mentioned often in the context of not only forest farming but other types of agroforestry practices as well (see Chapter 13.3). The *Specialty Crop Competitiveness Act of 2004* and the *Food, Conservation, and Energy Act of 2008* define specialty crops as "fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture)." Eligible plants must be intensively cultivated and used by people for food, medicinal purposes, and/or aesthetic gratification to be considered specialty crops. Agroforestry practices enable landowners to generate income from the production of a wide range of conventional and specialty products while simultaneously protecting and conserving soil, water, and other natural resources (Chamberlain et al. 1998; Josiah et al. 2004; Gold et al. 2009). Products from agroforestry practices, including specialty or nontimber forest products, are derived from trees within forests, or in myriad combinations with trees or shrubs, crops, and/or animals (Garrett 2009; Mori et al. 2017). Examples of developing specialty crop industries using an agroforestry system include eastern black walnut, Chinese chestnut, pecan, American elderberry *(Sambucus canadensis),* American hazelnut (*Corylus americana*), and pawpaw (*Asimina triloba*); see Mori et al. (2017) for a detailed account. Although specialty crop production using agroforestry is projected to have great potential in the US, serious challenges posed by the lack of adequate knowledge networks and supporting industry infrastructure must be overcome to advance the program.

Organic crops. Another notable and related activity in the context of Forest Farming and agroforestry is the increasing interest in Organic Farming. According to the Organic Trade Association (OTA), the Agriculture Marketing Service (AMS), and the Economic Research Service (ERS), there has been enormous growth in the market for locally grown and organic food products in both fresh and value-added form within the US (Green and Dimitri 2009). Organic and locally grown foods are perceived by consumers as healthier and safer for both people and the environment. With increasing concerns about links between food quality and human health, retail sales of organic food in the United States have grown 20 percent annually since 1990. This has generated considerable interest in alternative local sources of food and sustainable agricultural practices. Jose (2009) reported that the pace of conversion of cropland from conventional to organic has not kept up the demand for organic food, and that consumers shop at farmers' markets primarily because of product quality and the fact that the food is locally grown. Brown (2003) reported that the consumers are willing to pay 5% to 10% premium price to food produced locally by organic farmers because of the better quality and freshness of the produce Aguilar et al. (2009, 2010) showed that consumers were 15 to 20 times more likely to choose locally grown Missouri chestnuts, and the preference to organically grown over conventionally grown chestnuts was five-time higher. Consumer skepticism in the United States about the safety of the global food system has been confirmed in a nationwide survey conducted by the Leopold Center (Pirog and Larson 2007). This trend is reflected by the increase in the number of farmers' markets in the USA from 1,755 in 1994 to 6,132 in 2010. All these trends are indicative of the tremendous opportunities for including agroforestry as an organic farming option to produce fruits, nuts, and vegetables from small as well as large farms. Intensively managed agroforestry practices can be designed to incorporate a diverse number of locally grown and/or organic crops in both as fresh and value-added products for growing markets. Agroforestry practices also offer a very favorable platform and environment for promoting organic agriculture and specialty crops (Stamps and Linit 1997; Brandle et al. 2004).

Urban Food Forests. As noted in the introductory part of this chapter, *Urban Food Forests* (UFF) that are similar to the Urban Food Forestry in the tropics (Clark and Nicholas 2013) (Chapter 11, Section 11.5.4) are emerging as a form of agroforestry in the temperate regions of the world as well (Bukowski and Munsell 2018; Jose 2019). Composed of a mixture of different tree and shrub species, these multistrata systems integrate elements of urban agriculture, urban forestry, and the principles of agroforestry to improve the sustainability and resilience of urban ecosystems. The practice, now included as an agroforestry practice in North America (Figure 10.14), is also being recognized in the UK (Figure 10.23). The UFF in both the temperate regions and the tropics have similarities to the tropical homegardens, but the temperate UFF do not usually have the herbaceous crops and domestic animals that are integral components of the tropical homegardens, nor are they concentrated around the household on small parcels of land as in the tropics (Chapter 7). A growing number of organizations and city governments are adopting this concept in the megacities of the tropics and urban environments in the temperate region,

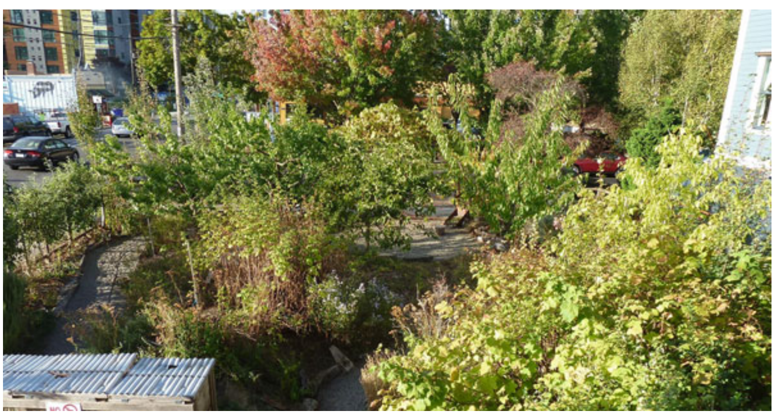

Figure 10.14 Urban Food Forest: Fargo Food Forest Portland, Oregon, USA. A paved parking lot was removed, the site was designed to mimic the uneven terrain of a forest floor and gravel pathways were engineered to channel water into an underground dry-well. Apples, pears, and other fruit trees line the sides of the food forest while an herb garden, composting area, and native bird habitat surround a patio of tables and umbrellas used by the adjacent cafe. (Photo: Catherine Bukowski of www.communityfoodforests.com)

primarily because of their importance in ensuring food security of a rapidly growing urban population, particularly the poor (Jose 2019) (Figures 10.15 and 10.16).

[Note: The authors thank S. Jose, University of Missouri, USA, for a critical review of the draft and valuable suggestions for improvement of Sections 10.2 (Historical Perspectives) and 10.3 (Agroforestry in North America)].

10.4 Agroforestry in Europe

10.4.1 Traditional Practices: The *Dehesa* System

A traditional and widespread agroforestry system that survived the push for tree eradication from farmland in the late 1900s is the well-known *Dehesa* system in the southwestern part of the

Figure 10.15 A silvoarable agroforestry systems involving walnut (*Juglans nigra* x *regia*) at Montpellier, France. (Photo: BM Kumar)

Figure 10.16 Silvoarable agroforestry in Europe: Vineyard agroforestry involving *Sorbus domestica* in Montpellier, France. (Photo: BM Kumar)

Iberian Peninsula (southern and central Spain and southern Portugal) with an estimated area of 3.1 million ha (Moreno et al. 2007; Moreno and Pulido 2009; Mosquera-Losada et al. 2012). A dehesa, known as *montado* in Portugal, is a multifunctional agrosilvopastoral system and cultural landscape (Figures 10.17, 10.18, 10.19, and 10.20). The term dehesa is derived from the Latin "defensa" referring to land that is fenced and usually allocated as pasture. Dehesas may be private or communal properties and are used primarily for grazing; they also produce a variety of products, including non-timber goods such as animals (wild game), mushrooms, honey, cork, and

Figure 10.17 A general view of the dehesa (agrosilvopastoral) landscape in Galicia, Northwestern Spain. (Photo: M. Rosa Mosquera-Losada)

Figure 10.18 A stand of debarked cork oak *(Quercus suber)* trees in the dehesa landscape in Northwestern Spain. During the dry season (when the photo was taken) there is no understory (grass) vegetation and therefore animal grazing. The tree bark is harvested regularly for commercial cork production and the debarked tree trunk is treated with insecticides and fungicides to protect it from insect and fungal damages. (Photo: Vimala Nair)

Figure 10.19 The montado (dehesa) system in Portugal. (Photo: João Palma, AGFORWARD)

Figure 10.20 Mixed livestock in a montado (dehesa) – Portugal. (Photo: João Palma, AGFORWARD)

firewood. The stand density is 50–100 mature trees ha^{-1}, providing a tree cover of 5 and 20% (Joffre et al. 1988). The most common trees are deciduous oaks, primarily *Quercus ilex* and *Q. suber*, and to a lesser extent species such as *Q. faginea* and *Q. pyrenaica*. The *Quercus* species are preferred because of the value of their acorns as a feed resource for animals grazing underneath. Grazing and crop cultivation are common under the open oak canopy of this agrosilvopastoral system (Figure 10.18: During the dry season, when the photo was taken, there is no understory of grass and therefore no animals). Cattle and sheep are currently the most common grazing animals, although pigs are also important components during the autumn when acorns are the main feed resource for pigs. Grazing management is flexible but includes moving animals to field stubble and fodder sources during dry summer months, with concomitant resting periods for grasslands. In managed dehesas, oaks may be planted where tree cover is insufficient, and established trees are often pruned to improve acorn and wood production (Joffre et al. 1988). Numerous reports are available on the structure, function, management, and persistence of the dehesa system (Joffre et al. 1988; Moreno and Pulido 2009; Mosquera-Losada et al. 2012; Burgess et al. 2018). Other forms of silvopastoral practices in Europe include sheep grazing under various tree stands such as cherry (Figure 10.21) and in vineyards.

Figure 10.21 AF in Europe – Silvopasture – Sheep under cherry in northern Spain. (Photo: Michael den Herder, AGFORWARD Project)

10.4.2 Traditional Practices: Integrated Fruit-Orchard Agroforestry in Europe

As mentioned earlier in this chapter, land-use practices such as forest grazing and forest farming that are considered as forerunners to agroforestry have traditionally been practiced in some parts of Europe for centuries (Section 10.2 and Chapter 4, Section 4.6.) A somewhat similar system that is practiced on farmlands and fruit orchards is the animal grazing under traditional fruit-tree orchards in Europe, sometimes called *Streuobst* (Herzog 1998). It consists of common fruit trees such as apple (*Malus domestica*), pear (*Pyrus communis*), cherry (*Prunus cerasus*), plum (*Prunus domestica*), and apricot (*Prunus armeniaca*) on meadows or pastures that are either allowed to be grazed by cattle or sheep or mown and the grass being taken to animals in the stable. Typically, the trees are scattered in an irregular pattern at densities between 30 and 100 trees per hectare (Figure 10.22). They are often planted around villages ("*Streuobstgürtel*" in German) and on abandoned vineyards on south-exposed terrain, where light and temperature favor fruit tree production. Historically, they were often intercropped, but since the early 19th century, they were increasingly converted to silvopastoral systems, although the olive tree (*Olea europaea*) is still the most popular woody species in European silvopastoral systems (Papanastasis et al. 2009). The traditional fruit orchards occur across Europe, in the Mediterranean, Atlantic, and Temperate zones but with different fruit species depending on the climatic conditions (Herzog 1998). While apple and pear trees dominate in the UK, Northern France, Germany, Poland, and other temperate climates, cherry and apricot are more common in northern Spain, southern France, Italy, Turkey, and other places where the temperature is milder. In all regions, however, this agroforestry system has declined substantially since the 1950s because of the gradual shift in the overall land-use patterns consequent to rapid modernization and mechanization of agriculture and the "expansion" of villages to the adjacent areas (Eichhorn et al. 2006). Nowadays, table fruit production occurs mostly in specialized orchards with dwarf trees, while fodder production has also been intensified, often by replacing permanent grasslands with sown grasslands. This transformation of traditional fruit orchards to specialized fruit- and fodder production systems was promoted by government agencies and extension services and was welcomed by most farmers because of the advantages offered by mechanized, rationalized, and intensified production and marketing systems. However, as the traditional, integrated fruit-tree systems disappeared at increasing rates, nature-protection organizations and the public at large became aware of the loss of habitats for specialized orchard birds – and biodiversity in general – and of the changing landscape scenery. Private initiatives tried to maintain traditional

Figure 10.22 Traditional cherry orchards with cattle grazing in north-western Switzerland. (Photo: Felix Herzog)

fruit orchards by engaging volunteers for the management and maintenance of such orchards (e.g., www.nabu.de/natur-und-landschaft/landnutzung/streuobst/). Furthermore, the traditional ways of land-use systems were encouraged to be sustained by marketing techniques such as labeling or otherwise identifying the products with information about the origin of the products (mostly fruit juice or cider) and thereby attracting the consumers' attention and stirring their emotional links to specific regions. Examples are Protected Designation of Origin cider in Brittany (France, www.routeducidre-cornouaille.bzh), apple juice in Switzerland and Germany that is labeled as agroforestry product (e.g., www.hochstammsuisse.ch), or pastries with plums that have been created to maintain the traditional agroforestry landscapes by improving the marketing opportunities for the fruit (www.posamenter.ch). Those private initiatives were later supported by agri-environmental schemes that provide payments to farmers for maintaining traditional fruit orchards in many European countries. In Switzerland, for example, each agroforestry fruit tree is supported by an annual payment, which is supplemented by bonus payments if the agroforestry orchard meets minimum standards for biodiversity and is part of a regional ecological network (Herzog et al. 2005). In Germany and Austria, there are regular debates about whether "Streuobst" agroforestry systems should even be protected by nature protection laws. Such stringent regulations have, however, been not enacted or implemented for fear of backlash and resistance from farmers (Figure 10.23).

Recent research has focused on understanding and evaluating the production benefits as well as ecosystem services of the traditional fruit orchards, with attention to regulating services such as carbon sequestration, water quality, and soil protection (Kay et al. 2018) and cultural services such as landscape scenery (Junge et al. 2015). Based on an evaluation of the potential benefits, Kay et al. (2019) suggest that if those services were marketable goods, fruit orchards and other traditional agroforestry systems would become profitable again. Coincidently, there has been increasing interest among farmers and researchers to experiment with modern, fruit-tree-based agroforestry systems, particularly by combining fruit trees and crop- or vegetable production systems (Herzog et al. 2018; Lauri et al.

Figure 10.23 Forest Garden (UK). Large tree: *Alnus cordata*; Trees to the left: apricot; Smaller shrub: *Amorpha fruticosa*. Shrubs to the right: *Cephalotaxus harringtonia*, raspberries. On ground to the left: *Rubus nepalensis*. (Photo and description: Martin Crawford, Agroforestry Research Trust, UK)

2019). The "rediscovery" of this traditional agroforestry practice represents an emerging approach to sustainable intensification.

*(*The sub-section, 10.4.2, was contributed by Felix Herzog, Agroscope, Research Division Agroecology and Environment, Switzerland: felix.herzog@agroscope.admin.ch)*

10.4.3 Recent European Initiatives in Agroforestry

Many of such traditional practices, however, disappeared during the 20th century as trees were removed from agricultural land to facilitate land consolidation and mechanized intensified farming that became the order of the day during the post-World War II era. Furthermore, during the last part of the 20th century, the Common Agriculture Policy (CAP) of the European Union discouraged the presence of trees on farmlands, and CAP payments for crops or pastures were often reduced for parcels with scattered trees (including trees on the plot- and field boundaries). The eradication of these traditional systems led to several unfortunate consequences including loss of farmers' know-how of such practices, creation of monotonously uniform landscapes, and increased environmental problems such as soil erosion, water pollution, and biodiversity decline. As land-users and policymakers became increasingly aware of the disadvantages of the CAP policies on the one hand and with the growing enthusiasm in agroforestry around the world including North America on the other, there was a remarkable turn-around in the perception about the role and importance of trees on farmlands during the past two decades (2000–2019). Consequently, numerous pan-European agroforestry activities sprang up with the financial support of the European Union and national sources. The significant among them included the *SAFE* project, 2001–2005, the *AGFORWARD* project, 2014–2017, and the AFINET project 2017–2020.

The SAFE (Silvoarable Agroforestry for Europe) was a research project (https://www1.montpellier.inra.fr/safe/english/index.htm) with the participation of more than 70 scientists from eight European countries coordinated by INRA (Institut national de la recherche agronomique = the national agricultural research institute), France. It demonstrated that modern AFS were compatible with present-day agricultural techniques, but specific tree management schemes were necessary (such as tree alignment and stem formative pruning). It also showed that the average productivity of silvoarable systems (see Table 3.5 of Chapter 3 and Section 10.4.4 of this chapter for an explanation of the term) was higher than the combined productivity of separate tree and crop systems with productivity increases of up to 30% in biomass and 60% in final products. A key result was that tree-crop systems can capture more resources from the environment than sole stands of crop or tree systems. The project estimated that 90 million hectares of land in Europe were potentially suitable for silvoarable agroforestry and 65 million hectares would benefit from silvoarable plantations to contribute to the mitigation of some key environmental problems such as soil erosion or nitrate leaching. If 20% of the European farmers of these areas would adopt agroforestry on 20% of their farms, it would result in 2.6 million hectares of silvoarable agroforestry in Europe. The quality timber that would be available from this activity would help reduce the need for importing high-quality tropical timber.

The *AGFORWARD* (AGroFORestry that Will Advance Rural Development) project (www.agforward.eu) that involved about 820 stakeholders across 13 European countries developed and field-tested 40 agroforestry innovations (Burgess et al. 2018). These included cheaper methods of tree protection and guidance for establishing legumes in wood pastures. Innovations for agroforestry with timber plantations, olive groves, and apple orchards include the use of medicinal plants and a reduction of mowing costs. Innovations for integrating trees on arable farms included assessments of yield benefits by providing wind protection. Detailed reviews of existing policy and recommendations for future European agroforestry policy have been produced. Outputs of these projects also included numerous scientific and extension publications as documented in their respective websites (Santago-Freijanes et al. 2018a, b, c; Mosquera-Losada et al. 2018a, b).

The AFINET (Agroforestry innovation network) project (www.eurafagroforestry.eu/afinet/) is a major pan-European extension network involving more than 1500 participants from nine European countries focused on identifying the main challenges to extensive adoption of agroforestry in Europe. The main challenges so identified were linked to technical, economic, educational, and policy aspects, from which a set of 110 innovations were selected and showed as videos or a live handbook (www.agroforestrynet.eu) translated to three languages (Spanish, English, and Italian).

The enthusiasm generated by the progression of these major research and development efforts led to the creation of EURAF (European Agroforestry Federation (www.eurafagroforestry.eu/) that has 280 member entities from 20 countries across Europe and the initiation of a biennial series of EURAF Congresses that started in 2012. The proceedings of the conferences and other materials that are available online provide a rich resource base for the current status of agroforestry in Europe.

10.4.4 Current Status of Agroforestry Systems in Europe

As mentioned in Chapter 3 (Section 3.9), the North American model has been adopted for identifying distinct agroforestry practices in Europe. The EURAF has recognized five agroforestry practices that are somewhat similar to the North American practices: silvoarable or alley cropping, silvopasture, riparian buffer, homegardens, or kitchen gardens, and forest farming (Table 3.5). The major differences between the North American and European terms are that, in Europe, the term silvoarable is used as a synonym for alley cropping (Figures 10.15 and 10.16) and the term windbreak is not commonly mentioned in the literature; moreover, kitchen garden or homegarden is mentioned as a practice associated to urban or periurban areas. Silvoarable is defined as “Widely spaced woody vegetation intercropped with annual or perennial crops. Also known as alley cropping, trees/shrubs can be distributed following an alley cropping design with isolated/

scattered trees, hedges, and line-belts design" (Table 3.5). Conceptually, the kitchen garden is somewhat similar to the homegardens in the tropics (Chapter 7). Detailed descriptions of various agroforestry systems across Europe and research results from several investigations are available in several excellent publications. A notable one is the book *Agroforestry Systems in Europe* (Rigueiro-Rodriguez et al. 2009).

The biennial agroforestry conferences and other activities of EURAF have rekindled the interest in agroforestry across Europe and provided a valuable opportunity for studying and reporting both traditional and modern agroforestry land-use systems in different parts of Europe during the past two decades. For example, Papanastasis et al. (2009) described 40 prominent silvoarable and silvopastoral systems in Greece; the most common systems include species such as walnut (*Juglans regia*), almond (*Prunus amygdalus*), mulberry (*Morus alba*), poplars (*Populus thevestina*), olive (*Olea europea*), carob (*Ceratonia siliqua*) and fig (*Ficus carica*) with associated crops. The systems that involve cereal crops often become agrosilvopastoral as livestock graze the stubble after grain harvest (Yiakoulaki et al. 2005; Correal et al. 2009).

In the UK, the most promising new AFS are those where trees have a particularly high value, e.g., orchard intercropping systems, and systems where the presence of trees provides animal welfare and marketing benefits. Woodland grazing systems are also being encouraged within existing forests to increase understory diversity and the regeneration of some tree species. Other systems where the trees, crops, and animals are less closely mixed include shelterbelts to provide wind protection to animals and crops, tree belts to capture ammonia from intensive pig and poultry units, and riparian planting (McAdam 2006). A traditional pattern of mixed woodland and pasture, known as "bocage," is characteristic of parts of the UK and also common in France as well as the northern parts of Germany and the Netherlands. The increased planting of perennial species other than just grass in the UK (e.g., short rotation coppice, and vines) also provides farmers with more opportunities than a simple separation (zonation) between annual arable crops, grassland, and perennial woodland systems.

The "open orchards" are reported as the best-known extant agroforestry systems in Germany (Reeg 2011). Alley cropping agroforestry practices with fast-growing tree species such as poplar (*Populus* spp.), willow (*Salix* spp.), and black locust (*Robinia pseudoacacia*) as short rotation coppices are also recommended for biomass production and land rehabilitation (Grüenewald et al. 2007; Quinkenstein et al. 2009, 2012; Reeg et al. 2009). Shelterbelts, windbreaks, and forest belts are currently used in Hungary to protect crops and livestock from adverse factors such as strong winds (Takács and Frank 2009). A recent study that looked at farmers' attitudes toward tree shelterbelts in Kyrgyzstan reported that the small sizes of plots and the lack of information and external support were the main obstacles to the adoption of the agroforestry practice of tree shelterbelts (Ruppert et al. 2020). Open woodlands in other Mediterranean countries are also used as silvopastoral systems, with either oaks or carob trees as the dominant species (Joffre et al. 1988). Land management in these systems has not been well developed, nor is it well-documented in the literature.

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10.5 Agroforestry in Other Temperate/Industrialized Regions

10.5.1 Australia

***Redefining Agroforestry for Australian Farmers*:** We define Agroforestry as the commitment of resources by farmers, alone or in partnerships, toward the establishment or management of trees and forests on their land. This definition is based on the farmers' viewpoint that agroforestry should look and feel like forestry by farmers for farmers, and should reflect the diversity of interests, resources, and aspirations of the farming community" (Reid 2008).

Why Australian farmers plant trees: Many farmers recognize that integrating trees into the agricultural landscape can enhance farm production by protecting farm stock from both heat and cold stress and reducing evaporation from crops and pastures; tackle significant environmental issues including soil fertility and structural degradation, waterlogging, salinity, and soil erosion by wind and water; trap sediments and nutrient loads before they leach into waterways; enhance wildlife habitat, and improve landscape values. Since the turn of the century, there has been a greater interest in the role of trees in sequestering carbon to offset agricultural emissions (Reid 2017a, b).

Development of Agroforestry in Australia: Conventional plantation forestry is well established in Australia. Concentrated in a few strategic locations within the wet coastal zones, these plantations are owned almost entirely by corporations or state government agencies and based on a narrow range of species (*Pinus* spp. and *Eucalyptus* spp.). Until recently, few farmers had any direct experience, or interest, in growing trees for timber or other commercial products. In the early 1990s, however, the timber industry and government were faced with increasing community concerns about clearing native forest for plantation development, and poor returns from forests established on low-quality sites. This led to the clearance of farmland in high rainfall areas with the support of enabling government policy, resulting in a dramatic expansion of the industrial plantations over more than a million hectares within less than 15 years. Most of the new plantings consisted of eucalypt pulpwood plantations established on cleared agricultural land purchased or leased from farmers in the medium to high rainfall areas (Stephens 2001). This rapid change in land-use from agriculture to industrial forestry raised new concerns within the agricultural community, and several reports on the adverse social, economic, and environmental impacts of large-scale conversion of the family farms to monoculture plantations were published. During the same period, there was also an increase in integrated farm forestry, whereby tree growing was incorporated into farming, but their contribution to commercial timber production was relatively low (Alexander et al. 2000). The practice was perceived as a less controversial alternative to industrial plantation expansion. Thanks to the result of the rise of the Australian Landcare movement, the practice of farmers growing trees on their land gained acceptance as a means of solving problems related to land degradation (Alexander et al. 2000; Nelson et al. 2004). In adopting this practice, the farmers were more interested in growing trees in providing habitat for native wildlife than producing commercial forest products. This agroforestry approach that emphasized the design and management of tree planting on farms in ways that reflect the individual landholder's motivations, aspirations, resources, and risk profile was in stark contrast to that of many government agencies, whose focus was on the promotion of a set of pre-defined options (Reid and Deans 2009).

***Farmer-designed multipurpose agroforestry*:** The leading agroforestry practitioners in Australia are those who strategically integrate multipurpose plantings with their agricultural systems and family activities at the farm- or enterprise-scale, rather than at the paddock- or plot-level. The profitability and sustainability of a family farm is not simply a reflection of what occurs in one paddock. For example, most farms have some areas of relatively low agricultural productivity or sites in need of revegetation for land protection that can be excluded from grazing or cropping without reducing agricultural productivity. In many cases, trees planted on these sites will provide shade and shelter benefits that extend over much of the property. On flatter land, there may well be a case for having additional belts of trees that provide shelter benefits that offset the loss of productive land and any competition effects close to the trees.

By carefully designing and implementing revegetation and forest-management projects at the farm (rather than the paddock) level, agroforestry can provide a unique opportunity to enhance total productivity, environmental integrity, and ultimately the capital value of the whole farm. This approach to agroforestry is being supported by research that focuses on the processes of land degradation, the role of trees in protecting and enhancing agricultural production, and the production and marketing of tree products. Rather than provide cost-share subsidies to promote pre-defined agroforestry designs, effective public investment in agroforestry development focuses on farmer education, farmer-to-farmer networking, and improving dialogue between farmers, researchers, industry, and conservation groups. The result is a diversity of agroforestry activities across the farming landscape, which not only reflects the diversity inherent within the physical and economic landscape but also the diversity of interests and aspirations for those who make the decisions about how our land is managed.

*(*The Subsection 10.4.1., Agroforestry in Australia, was contributed by Rowan Reid, Forest Scientist and owner of the Bambra Agroforestry Farm, Bambra, Victoria, Australia; www: www.agroforestry.net.au; email: rowan.reid@agroforestry.net.au)*

10.5.2 New Zealand

Interest and initiatives in agroforestry started in New Zealand even before they started enthusiastically in North America: combined production of pasture and timber increased in the late 1960s as all suitable land was gradually placed in either agriculture or forestry use (Percival and Knowles 1983). A drought in 1968 also clarified the role of agroforestry, as farmers sought grazing opportunities in forests, and forest managers realized that grazing livestock would improve access for silvicultural work, reduce fire risk, and provide revenue (Knowles and Cutler 1980). The trend toward wider initial spacing and early pruning and thinning in radiata pine (*Pinus radiata*) plantations strengthened this approach. That was followed by considerable research on different aspects of this management system, including optimum planting density of trees (to facilitate maximum fodder production without reducing wood yield), weed control measures, evaluation of fodder trees in different management systems, and the use of secondary products such as stems, seeds, and fruit from these trees as potential supplements to traditional forage species (Byington 1990). These efforts led to the development of three distinct and viable silvopastoral types: forest grazing, timber belts, and trees on pasture. Radiata pine has proved to be the pre-eminent species for profitable agroforestry (Knowles 1991). Similar efforts with grazing trials have also been conducted in Australia with plantations of eucalyptus (Cook and Grimes 1977) and radiata pine (Anderson and Batini 1979; Anderson et al. 1988).

10.5.3 China

As mentioned in Section 10.2, China has a long tradition of practicing agroforestry; however, the term “agroforestry” was not translated into Mandarin until the mid-1980s. Indeed, Hong et al. (2017) reported that the official statistics about the prevalence of agroforestry systems in China are unclear because areas under cultivation in China do not distinguish sole crops from intercrops. Based on a village-level survey in 68 villages across six provinces in China in 2014 to document the prevalence of mixed-species cultivation systems, the authors (Hong et al. 2017) reported that intercropping was practiced on approximately three percent of the arable land in the surveyed villages, while agroforestry was practiced on approximately one percent of the arable land and one percent of the area of plantation plus forest land.

Today, China reportedly faces three serious and interlinked challenges: environmental degradation, population growth, resource depletion. Agroforestry has been widely recognized as a strategy for environmental amelioration and control of soil erosion in China (Zhang et al. 2008). Consequently, agroforestry systems such as homegardens (see Figure 11.13, Chapter 11), “four-side” plantations (trees around houses and along roads, canals and villages), and intercropping of agricultural crops with fruit and nut-yielding trees [e.g., Chinese date (*Ziziphus jujuba*), apple (*Malus* spp.), peach (*Prunus persica*) and pear (*Pyrus* spp.)] are practiced nation-wide. While silvopasture systems are more popular in northern China, the most common agroforestry practices in the temperate regions of China are silvoarable in nature such as paulownia (*Paulownia* spp.)-based intercropping and shelterbelt systems (Chang et al. 2018); see Figure 10.24 showing intercropping of tea (*Camellia sinensis*) under *Paulownia tomentosa* in Hubei Province at the Baoping Wang Paulownia Research and Development Center of the State Administration of Forestry and Grassland, China.

Most if not all agroforestry systems in China were developed by adopting the "three-in-one" approach, involving party cadres who set the targets, extension personnel who implement the policy, and farmers who carry out the actual work. As a result, most agroforestry systems are large-scale projects with more or less identical designs. Since the reform policies of the 1970s and 1980s, the government has devoted considerable attention and financial resources for afforestation programs, most notably "Three-North" afforestation or the Great Green Wall project (Section 10.3.3). Other similar ecorestoration projects include the protective forests in the mid-upper reaches of Yangtze river, coastal protection forests, "greenization" of plains, and "sand control engineering" (afforestation to control sand storms in northern China). To address the twin problems of environmental deterioration and rural poverty, China also initiated the "Grain For Green" (GFG) program in 1999. It is one of the largest land-use transition, watershed management, and poverty alleviation programs, covering 25 provinces/regions of the country. Also known as the "Conversion of Cropland to Forest Program" (CCFP), it provides food and cash subsidies to farmers for planting trees on their land and provides degraded land to rural families for restoration.

10.5.4 Southern Parts of Latin America

In Latin America, where more than 90 million ha of land is under the pressure of environmental degradation consequent to forest conversion to cattle ranching (FAO 2018), silvopastoral systems have become an economically and ecologically attractive land use practice (Figure 10.25). While the enthusiasm in silvopastoral systems is prevalent throughout the continent, it is particularly evident in the southern parts of South America comprising Argentina, Chile, and southern Brazil – a region that does not figure prominently in agroforestry literature. In a multi-

Figure 10.24 Intercropping of tea (*Camellia sinensis*) under 8-year-old *Paulownia tomentosa* in Chibi City, Hubei Province, China (Source: Baoping Wang Paulownia Research and Development Center of the State Administration of Forestry and Grassland, China; Courtesy: Scott Chang, Univ of Alberta, Canada)

Figure 10.25 Silvopasture in southern South America. Integration of *Eucalyptus grandis* and temperate grass with beef cattle in Paraná State, Brazil; Varella et al. in Piri et al. eds (2016). (Photo: Pablo Piri)

authored compendium, Peri et al. (2016) have described the major developments in various management and production attributes as well as the ecological and socioeconomic benefits of these systems in this region. Almost all the systems described in the book incorporate exotic tree species or managed native forests into farming systems that combine trees and livestock on the same unit of land, suggesting that silvopasture is the major agroforestry practice in the region. It is worth mentioning that the term ICLF (Integrated Crop Livestock Forestry Systems), a term that is gaining popularity primarily in Brazil and other parts of S. America (see Section 9.6), is used almost synonymously with silvopasture and sometimes agroforestry in these descriptions.

10.6 Concluding Remarks

Overall, interest in agroforestry as a desirable land-management option in the temperate zone, especially North America, increased steadily during the last two decades of the 1900s. This was marked by the initiation of new research and academic programs in agroforestry in some leading universities and by the national research organizations such as the USDA, especially the US Forest Service and the NRCS (Natural Resources Conservation Service). With time, however, the momentum seems to have slowed down since the early 2000s. While some of the on-going programs continued, new initiatives and activities slowed down. Despite the apparent attractiveness of agroforestry systems, landowners generally do not seem to be enthusiastic in adopting the practices. The success in the adoption of new land-management systems depends on a variety of factors other than their biological performance. On the agricultural front, the profitable sole-crop farming systems developed with excellent government support over several decades cannot easily be replaced. On the forestry side, low wood prices and marketing difficulties may reduce the potential revenue from timber harvests, regular spraying for persistent diseases of tree species may damage annual crops and pastures, and increasing ownership of tree plantations by part-time farmers or absentee landowners may prevent the cultivation necessary for annual crops. Such problems underscore the need to understand owner objectives, infrastructure needs, and cultural issues before agroforestry systems are widely accepted.

Rapid strides, however, are being made in agroforestry across Europe, where environmental issues have become high on the political and social agendas since the turn of the century. As in most other regions of the world, the separation of forestry from agriculture (including livestock production) is the main impediment to promoting combined systems. Lately, however, policy-makers in Europe have become environmentally more appreciative of the value of silvopastoral and silvoarable systems that have been experimentally tested and proven valuable in several European countries, and support to agroforestry on farmlands is increasing. This welcome change could eventually lead to similar policy changes and major national initiatives in favor of agroforestry across the Atlantic as well as in other temperate regions too.

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Other Agroforestry Systems and Practices

11

Contents

Abstract

This chapter deals with a vast array of complex and diverse systems and practices that are little known outside the limited regions where they are practiced but are revered by the local inhabitants for their multiple products, outputs, and services. The term *Cinderella agroforestry systems* is used to refer to such “downtrodden” or little-explored systems. Some noteworthy examples of tree planting activities known by similar-sounding terms had been promoted by the traditional forestry departments in the 1990s. They all had the common underlying theme of the involvement of (local) people in planting, managing, and utilizing trees on farmlands (farm forestry), community lands (community forests), and socially and openly accessible lands such as the sides of roads, railways, and canals (social forestry). Fuelwood trees, fodder trees, medicinal and aromatic plants, trees outside forests,

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urban food forestry, permaculture, and carbon farming are some other specialty groups of trees and land-use practices that offer a variety of products and ecosystem services. These time-tested systems are intricately intertwined with the cultural and societal heritage of the practitioners and are repositories of ecological wealth providing diverse social and economic benefits.

11.1 Introduction

A key aspect of agroforestry research-and-development efforts during the early stages (the 1980s and the 1990s) was on understanding the undocumented local knowledge on the multitude of traditional agroforestry systems and incorporating their underlying principles in the design of improved systems and technologies. These efforts led to various analytical descriptions of the major types of agroforestry systems (AFS) and the development of some improved technologies, as summarized and presented in the first 10 chapters of this book.

In addition to those better-known systems, a vast array of complex and diverse systems and practices exist, many of which are seldom known outside their places of occurrence. Nair et al. (2017) used the term *Cinderella agroforestry systems* to refer to such "downtrodden" or little-explored systems. While some of these systems or technologies have been documented, there are several others, on which even qualitative descriptions are lacking. Their management and utilization involve various on-farm agroforestry approaches, including food- and fodder trees and silvopastoral practices, fuelwood lots, scattered multipurpose trees on farmlands, planting trees for soil conservation and degraded-land reclamation, and the use of trees as windbreaks and for combating desertification. Additionally, there are some other noteworthy examples of tree planting activities managed by traditional forestry departments and known by terms such as *farm forestry*, *social forestry*, *community forestry*, *trees outside forests*, and so on, most of which involve agroforestry principles (Nair 2007). This chapter will focus on such systems and practices under the broad term "Other agroforestry systems and practices."

The trees and other woody perennials used in such little-known systems provide a myriad of products and services. Some are relatively production-oriented (producing a variety of products such as food for humans and animals, fuelwood, specialty products, etc.) and others are relatively "service-oriented" (providing ecosystem services such as climate-change mitigation, control of soil conservation and land degradation, rehabilitation of "problem" soils such as saline and waterlogged soils, and many other environmental services). Many systems, especially most of those listed as the *Cinderella systems*, provide both the production and service functions. In the following pages, we will consider such systems and their unique production and service attributes. It needs to be noted that the multifunctional characteristics of these systems are not different from those of the "major" agroforestry systems emphasized throughout the book.

11.2 Cinderella Agroforestry Systems

As mentioned above, the term "Cinderella Agroforestry Systems" was coined to describe the underexploited and "forgotten" agroforestry systems and to highlight their potentials (Nair et al. 2017). The word *Cinderella*, made popular and even immortal by Walt Disney Production's movie by that name, has, by analogy, become known to refer to an individual whose attributes were unrecognized or one who unexpectedly achieved recognition or success after a period of obscurity and neglect. Leakey and Newton (1994) used the term *Cinderella Species* to refer to the "really indigenous multipurpose trees, the products of which have traditionally been collected, gathered, and utilized by humans, and are still of enormous importance to many people around the tropics for food and nutritional security and welfare." The underlying concept of Cinderella systems is similar: relatively little-known, location-specific agroforestry systems that although have traditionally been practiced around the world for their multiple products and services have largely been neglected in the study and push for "improved" agroforestry practices and technologies. The information base on such systems is scarce and mostly anecdotal. Subject to this limitation, Nair et al. (2017) summarized the principal attributes of 16 such systems from Asia, Africa, Latin America, as well as the temperate industrialized world as presented in Table 11.1. Broadly, these systems, which are little-known outside their areas of occurrence, are unique in terms of their production, environmental, and sociocultural attributes, none of which, however, has been reported in quantitative terms. While sustainability, multi-functionality, and high sociocultural values are their common strengths, low levels of production, and lack of research- and technology inputs to improve the system are the major deficiencies. These are not "new" systems. They all have been built upon the native assets of land, water, and other resources, relying on local varieties and indigenous knowledge over centuries. The indigenous trees that are central to each of the systems included in Table 11.1 have not been planted or "tailored" to any specific pattern of planting, spacing, or management and are therefore usually seen as dispersed stands on the landscape. This deficiency restricts the application of quantitative analytical procedures to quantify and compare their attributes and suggest data-based improvement-strategies.

In general terms, it can be argued that the Cinderella agroforestry systems fulfil the requirements of all three "pillars" of sustainability – economic, ecologic, and social. It is irrefutable that the practitioners of these systems exist at low levels of economic development. That being the case, sustainability should not be seen in isolation; it needs to be meshed with development objectives for attaining the well-being of humans as well as the ecosystems that support them. The Millennium Ecosystem Assessment reports (MA 2005: Chapter 19) have "accepted" that economic advancement typically comes at costs to the environment, and framed the concept of *Sustainable Development* as the balancing of this objective of preservation with economic advancement. The extent to which each of the Cinderella AFS considered in this study fulfills the parameters of Sustainable Development, though worth examining, is not attempted here.

11.3 Agroforestry Systems for Production of Subsidiary Commodities

The term subsidiary commodity is used here to refer to such items as fodder, fuelwood, medicines, and a whole array of specialty products that are produced in agroforestry systems that are not considered the "primary" products of farming. Some or many of them may not enter into international trade and commerce and, therefore, their value and importance are not fully appreciated. Although not specifically mentioned, many trees in such systems also contribute to food production and food security directly or indirectly (Chapter 23). The following sub-sections focus on AFS that have traditionally supplied the farm families with valuable "agroforestree" products such as fuelwood, tree fodder, and medicines, the economic value of which is seldom recognized because they are not commercially traded. The emphasis in these sub-sections is on the systems that are dominated by such traditional trees; the dominant tree- and other woody-perennial components of the systems are considered individually in Chapter 13.

11.3.1 Fuelwood Trees in AFS

Globally, wood accounts for about 6% of the total primary energy supply and it is the foremost source of renewable energy with more than two billion people depending on it for their domestic energy requirements, especially in the developing countries (http://www.fao.org/forestry/energy/en/). Private households' cooking and heating with woodfuels account for about a third of the global renewable energy consumption, making wood the

Table 11.1 Characteristics of some Cinderella agroforestry systems around the world

System Type	Name	Geographical Distribution and Climatic Features	Structure: Major Components	System management features	Function: Outputs (production	Reference
ASIA-PACIFIC						
Multipurpose tree (MPT) integration with rice cultivation	The Chhattisgarh system	Chhattisgarh, India; 21.27° N, 81.60° E	Tree: *Acacia nilotica* Crop: Rice and catch crops such as sesamum (*Sesamum indicum*) on field bunds (raisers)	Optimum tree spacing: 10 m by 10th year. Farm animals have a role in tree generation. Trees pruned to maintain straight boles	Tree products: fuel wood; wood for fencing, small timber, etc.; gum. Crops: Rice and catch crops	Viswanath et al. (2000)
MPTs with dryland/rain-fed crops	Scattered trees in pasture lands	Tamil Nadu, India - 11.01° N, 76.97° E (Coimbatore); annual rainfall ~600 mm during August to Nov	Tree: *Acacia leucophloea* and other MPTs Crops: *Pennisetum glaucum* and *Dolicos uniflorus*	*A. leucophloea* regenerates when land is plowed after first rains. Crops for grain or fodder. Tree-stand density thinned to 60–100 per ha	In addition to crop yields, trees provide ~100 kg tree pods /ha annually; also fuel wood, charcoal, fruit and fodder	Jambulingam and Fernandes (1986) and Kumar et al. (2011)
	The “khejri” system	Rajasthan, India; 26.57° N, 73.84° E; about 400 mm rainfall in 3–4 months per year	Tree: *Prosopis cineraria* (“*Khejri*”); Crops: Millets	Lopping of the tree just before the cropping season to reduce shading on understory crops	*P. cineraria* foliage and pods as forage; millets (grains) for home (human) consumption	Shankarnarayan et al. (1987) and Tejwani (1994)
	Ficus-based system	Mandya district, Karnataka, India; 76.19′–76.20’ S and 12.13′–13.4′ E; 700 mm rain per year during June to September	Tree: *Ficus* spp. Crops: millets, pulses, maize, and oil seeds	*Ficus benghalensis* is the major tree species; trees regenerated by rooted cuttings; stand density: 16–20 trees/ha; crops grown in rainy season; animals (cows) reared for milk production	Food grains, fuel wood, timber etc. to the household, provides dairy products, farmyard manure and green manure	Dhanya et al. (2012)
Pacific Islands agroforestry	Specialty crops and trees	Pacific Islands; lowland humid tropics; well-distributed rainfall of >1500 mm per year	Various tropical fruit- and nut trees as the upper-story; shorter trees as second story, and crops, mostly tuber crops in the lowest-story; ornamentals along border	Upper-story fruit trees are pruned to allow sunlight for lower story species. The understory is allowed to return to fallow for a period ranging from 4–10 years, retaining only fruit trees	Tree products: fruits, vegetables, small timber, fiber, flowers for decoration and ornamentation; Crop products: Food, medicine, beverages	Elevitch (2007, 2011)

(continued)

AFS for salt-affected-soil reclamation	Bio-drainage system	Northwestern India and other salt-affected lands: globally, one billion ha of arid and semi-arid areas remain barren due to salinity or water scarcity	Salt tolerant trees (e.g., genera *Acacia, Atriplex, Casuaraina, Eucalyptus, Prosopis*) and many common crops/grasses	Various location-specific management practices	Tree products (timber, depending on species), food crops, and animal fodder	Dagar and Minhas (2016)
AFRICA						
Intercropping and silvopastoralism	The Parkland system	West African dry lands; unimodal rainy season of 3–4 months; the rest are long, dry, extremely hot periods; rainfall varies from 300 to 800 mm per year	Trees: *Faidherbia albida,Vitellaria paradoxa* (Shea nut tree), *Parkia biglobosa* (African locust bean), *Adansonia digitata* (Baobab), *Balanites aegyptiaca* (Desert date)	Rain-fed, smallholder cultivation of staple cereals (mostly millets), and extensive silvopastoralism with free-roaming animals; relatively even-aged stands of trees/shrubs, 40–60 per ha	Tree products: Parkland products eaten when crops have failed. Butter extracted from *V. paradoxa*; fiber from *A. digitata*	Boffa et al. (1999)
Homegardens	Global Heritage AF systems of E. Africa: “The Chagga”; Matengo Ngoro-Pit”; and “Ngitiil”, Tanzania	The Chagga in the foothills of Mt. Kilimanjaro, 1000 m asl.; the Matengo Ngoro-Pit system in the highlands, up to 2000 m; the Ngitili in western Tanzania, 1000 m	In the Chagga, tall trees (e.g. *Cordia abyssinica, Albizia* spp.) in upper-story; banana, coffee in the second-story; food and fodder crops, cardamom, and medicinal herbs in lower-story	Spatial arrangement is irregular and appears haphazard with the trees/ shrubs and food crops intimately mixed. Vertical zonation can be distinguished. Intensive management practices followed	Timber, fuelwood, fodder, medicinal plants, nuts and cash crops; various spices such as cardamom, black pepper, and cloves	Kitalyi et al. (2013) and Kato (2001)
	Compound Farms of West Africa	Southeastern Nigeria; 4°–7° N; 5°49′–9°39′ E; lowland plains to 200 m a.s.l.; 1250–2500 mm bimodal rainfall	Food crops (yams, plantain, maize, etc.) with various fruit trees (*Treculia africana, Dacroydes edulis, Pterocarpus*), and animals	No definite planting patterns; trees of various heights are mixed with food crops in the understory to give the typical multistory configuration	Various products for home consumption such as yams, tubers, and other food crops; fruits; and animal products; timber for sale	Okafor and Fernandes (1987)
LATIN AMERICA						
AFS in Central America	The Quezungal system	Southern part of western Honduras; 88°30’ W and 14°10’ N 200–900 m a.s.l.	*Cordia alliodora* is a common tree, pollarded to 1.5 m; crops include	Naturally-regenerated and pollarded shrubs and trees exist in association	Fruits, timber, crops (mostly for domestic consumption)	Hellin et al. (1999).

(continued)

Table 11.1 (continued)

System Type	Name	Geographical Distribution and Climatic Features	Structure: Major Components	System management features	Function: Outputs (production	Reference
			maize, sorghum, and beans; natural regeneration of trees	with traditional agroforestry components such as high-value timber and fruit trees		
AFS in Brazil	The Riberno system	Peruvian Amazon (lowland humid tropics)	Swidden fallow system: forest clearance followed by homegardening	Forest clearance, cultivation of agri crops (esp. food crops such as cassava, yam, plantains, rice); fruit trees	Food crops, fruits, timber; pineapple grown commercially	Padoch and deJong (1987) and Denevan and Padoch (1988)
	AFS in NE Brazil	Vast land area of ~1.5 million km^2, from 15°S to 1°S; mostly semiarid; rainfall varies widely from 300–1000 mm/year	Silvopastoral systems of grazing under tree crops such as cashew, coconut, and carnauba palm (*Copernicia prunifera*)	Common fodder grasses are ginger grass (*Paspalum maritimum*) and African Guinea grass (*Panicum maximum*)	Production of commercially valuable tree products; income from animal rearing	Johnson and Nair (1985) and de Almeida et al. (2013)
	Amazonian systems	The vast Amazonian humid tropical lowlands region of South America (Brazil, Peru, Colombia, Venezuela, Guyana, etc.)	Fruit trees and various palms and cacao; also various timber trees and Brazil nut (*Bertholesia excelsa*); field crops: cassava, yams, beans, plantains, etc.	Fruit trees and other trees planted around house; seedlings usually grown in house gardens; seeds of fruit trees interplanted with field crop	Multiple outputs from a variety of trees, palms, shrubs, and food crops offer food and nutritional security and cash income	Miller and Nair (2006)
TEMPERATE ZONE (INDUSTRILAIZED REGIONS)						
Fruit-tree based systems	*Streuobst*	Western Central and Eastern Europe	Fruit Trees: Various temperate fruit- and nut trees such as apple, plum, pear, peaches, walnut, almond, sweet chestnut, and fig; understory: pasture grass	Tall trees of and various fruits are dispersed on croplands, meadows and pastures in irregular pattern; management is usually better done in midsize farms	Fruit yield	Herzog (1998)

(continued)

	The Chania system, Greece	Greece (and other parts of southeastern Europe)	Cereals intercropped with fruit trees. Fruit trees: olives, sweet chestnut, walnut; intercropping. Also silvopastoral systems involving goats and cattle	Widespread practice since first millennium BCE. Leaf and twigs cut from trees used as animal fodder, esp. in winter	Fruits, cereals, animal products	Papanastasis et al. (2009)
Traditional AFS of Canada	No special name; but quite a few local activities	Throughout Canada (all five provinces)	Tree intercropping, farm woodlots, forest farming with ginseng, collection of wild mushrooms and other NTFPs, riparian woody buffers, limited scale forest grazing	Low intensity operations	Tree products, mushroom and other NTFPs	Thevathasan et al. (2012)

Source: Adapted from Nair et al. (2017), *a.s.l.* above mean sea level, *NTFPs* non-timber forest products most dispersed source of energy in the world, the term woodfuel being used as a broad term including firewood, charcoal, chips, sheets, pellets, and sawdust. With climate change and energy-security concerns looming large on our horizons, wood energy has acquired high prominence today (FAO 2016).

The fuelwood supply situation is alarming in many regions of Sub-Saharan Africa where the production potential of the dry ecosystem is inherently low and the demands are always on the increase (Figure 11.1). In many rural societies in developing countries, the collection of fuelwood cooking is often considered the woman's job. Harrowing tales and photos are available in plenty describing the long distances that the African women and children have to trek in search of the declining stock of firewood and the drudgery of traditional modes of transporting it from points of collection to consumption (Figures 11.2 and 11.3).

Farms, homegardens, village woodlots, small plantations on private or government lands, and trees or shrubs alongside roads, railway tracks, canals, and ponds, collectively known as "trees outside forests" (TOF: Section 11.5.6) are the key sources of woodfuels for rural communities in the developing countries). Homegardens in South and Southeast Asia with a wide spectrum of trees and shrubs are a case in point. According to some estimates, about 51% to 90% of the fuelwood collected in these regions are derived from homegardens (Torquebiau 1992; Ewel 1999; Kumar and Nair 2004). Other prominent land-use systems with potential for fuelwood production include woody perennial plantation

Figure 11.1 Fuelwood scarcity is an acute problem in many parts of Sub-Saharan Africa. Some argue that the peasant farmers may have to use a portion of their farm produce to cook the remaining portion. Throughout the region, it is common to see small pieces of fuelwood being stacked up for sale on roadside, as this photo from Mali shows. (Photo: PKR Nair)

Figure 11.2 Harrowing tales and photos are available in plenty describing the long distances that the African women and children go in search of the declining stock of firewood. The picture from Tanzania shows children headed from a dwindling hillside forest about 2 km behind them to the Monduli market about 2 km ahead. (Photo: Clifton Hiebsch)

agricultural systems, border planted trees, live fences, parkland agroforestry systems, and the like. Fuelwood also can be grown like a crop in tree plantations. Fast-growing multipurpose species such as *Acacia*, *Calliandra, Casuarina, Gliricidia, Leucaena, Prosopis,* and *Sesbania* (Chapter 13), some of which are also valuable fodder species, are amenable for fuelwood harvest every few years, with prospects for one or more "coppice" cycles. Scientific reports on the quantity and quality of biomass fuels produced and/or their extraction methods are scarce. Some parameters of the heat of combustion values (calorific values, kJ g^{-1} dry weight, of different parts of some agroforestry trees and shrubs commonly used in India) have been compiled by Kumar (2006). Species profiles of many of the common fuelwood species are included in Chapter 13.

11.3.2 Fodder Trees in AFS

As mentioned in Chapter 9 (Section 9.2, Figure 9.1), domestic animals are an integral component of smallholder farming systems and are often counted as a measure of wealth in many rural societies. These include not only conventional milk- and meat-producing animals (cattle and goats) but also sheep and draft animals such as camels and mules that are used for farm operations and hauling goods. They are traditionally allowed to graze on open woodland and community woodlots but are also often stall-fed with cut-and-carry fodder from fodder trees grown on farms and farm boundaries (Figure 11.4 and 11.5; see also Figures 9.9 and 9.10 in Chapter 9). Descriptions of the various forms of silvopastoral systems in the tropics and the

Figure 11.3 Another tedious way of transporting the precious firewood, in Mali. (Photo: PKR Nair)

temperate regions are included in Chapters 9 and 10, respectively. Numerous fodder producing trees, just like firewood trees, are also components of many Cinderella systems and other little-known localized agroforestry systems; species profiles of several of them are included in Chapter 13.

11.3.3 Medicinal and Aromatic Plants in AFS

Medicinal and aromatic plants (MAPs) play an important role in the healthcare of people around the world, especially in developing countries. Human societies throughout the world that depended on plants for treating human and livestock diseases until the advent of modern medicine have accumulated a vast body of indigenous knowledge over centuries on medicinal uses of plants. About 80 % of the population of most developing countries still use traditional medicines derived from plants for treating human diseases (de Silva 1997). China, Cuba, India, Sri Lanka, Thailand, and a few other countries have endorsed the official use of traditional systems of medicine in their health care programs. Notable Indian systems of traditional medicine such as *Ayurveda*, *Sidha*, and *Unani* entirely, and homeopathy to some extent, depend on plant materials or their derivatives for treating human ailments (Prajapati et al. 2003). Many among the educated in Asian and African countries use traditional medicines for reasons of the firm belief that they are more effective than modern medicine for certain chronic diseases, they do not have side effects of some of the modern medicines, and/or for economic reasons. Thus, in many societies, traditional and

Figure 11.4 Intensively pruned toona trees (*Toona ciliata*), known as Indian mahogany and Australian cedar and used also as an animal fodder, on the boundaries of a plot of cowpea plants (*Vigna unguiculata*) in a *Chagga* homegarden near Mt. Kilimanjaro, Tanzania. (Photo: BM Kumar)

Figure 11.5 "Cut-and carry" fodder production to feed domestic animals that are penned in small sheds adjoining the farmer's dwellings. The photo from Kenya shows *Calliandra calothyrsus* and Napier grass (*Pennisetum purpureum*) grown on the farm boundary that will be pruned periodically and the foliage taken to the animals. (Photo: ICRAF/World Agroforestry)

modern systems of medicines are used independently.

About 12.5% of the 422 000 plant species documented worldwide are reported to have medicinal values; the proportion of medicinal plants to the total documented species in different countries varies from 4.4% to 20% and the total number of MAPs in international trade is around 2500 species worldwide (Schippmann et al. 2002). The global importance of MAP materials is evident from a huge volume of trade at national and international levels: average global export in medicinal plants for the 14 years from 2001 to 2014 was 601,357 tons per annum valued at USD 1.92 billion (Vasisht et al. 2016). Japan and Korea are the main consumers of medicinal plants, whereas China and India are the world's leading producing nations. Forests are the primary source of these plants, and forests provide a wealth of highly prized MAPs throughout the world (Shackleton and Shackleton 2000). The increasing demands for medicinal plants by people in developing countries have been met by indiscriminate harvesting of spontaneous flora including those in forests (de Silva 1997). Over-exploitation of these species is leading to substantial depletion of natural resources and narrowing of their genetic base. Rao et al. (2004) reported that 16 medicinal plants including the highly valued *Atropa acuminata*, *Dioscorea deltoidea,* and *Rauvolfia serpentina* were listed as endangered species in the northwestern Himalayas, although they are not currently (2020) listed in the IUCN Red List (of endangered species): https://www.iucnredlist.org/search?query=saraca%20indica&searchType=species. The most vulnerable species are popular, slow reproducing species with specific habitat requirements and limited distribution. Although many species are employed in traditional medicine, the number of MAP species currently in cultivation for commercial production does not exceed a few hundred worldwide. For example, the species cultivated are only 100 to 250 in China (He and Sheng 1997), 38 in India (Prajapati et al. 2003), and about 40 in Hungary (Bernáth 1999). Some of this information may well be obsolete. For example, in India, the National Medicinal Plants Board, a Government of India agency established to promote the medicinal-plants sector, is currently (2020) reported to provide subsidy at varying levels for defraying the production cost of 95 priority MAP species (https://www.nmpb.nic.in/content/prioritised-list-medicinal-plants-cultivation). Many of these species are valued for poles, fuelwood, fodder, fruit, shade, and/or boundary demarcation and their medicinal value is secondary.

The MAPs growing in forests require (or tolerate) partial shade, moist soils high in organic matter, high relative humidity, and mild temperatures, and these conditions can be provided by agroforestry systems such as the shaded perennial systems and homegardens (Rao et al. 2004). Cultivation of such MAPs can be taken up in thinned forests and cleared forest patches, and as intercrops in new forest plantations. In China, the cultivation of medicinal plants has been an age-old practice under the name of "silvo-medicinal" systems. In northeast China, ginseng (*Panax ginseng*) and other medicinal plants are grown in pine (*Pinus* spp.) and spruce (*Picea* spp.) forests; in central China, many medicinal plants are planted with *Paulownia tomentosa* and in southern China medicinal herbs are often planted in bamboo (*Bambusa* spp.) and Chinese fir (*Cunninghamia lanceolata*) forests (Zou and Sanford 1990). The intensity of shade experienced by the understory MAPs growing in forests and tree plantations affects their growth and chemical composition. Growth, and bark and quinine yields of *Cinchona ledgeriana* grown on the Darjeeling hills, India, increased when it was associated with the shade of five species compared with that of a non-shaded stand (Nandi and Chatterjee 1991). The best yields were obtained when *C. ledgeriana* was planted under the shade of *Crotalaria anagyroides* or *Tephrosia candida* initially and *Alnus nepalensis* in the later stages. *Alnus* is planted at 3.6 x 3.6 m and is progressively thinned to 14.4 x 14.4 m as *C. ledgeriana* grows. The other factors that affect MAP yields are their growth cycle and nutrient inputs. *Dioscorea deltoidea,* grown in plantations of deodar (*Cedrus deodara*), fir (*Abies* spp.), and spruce

Table 11.2 Examples of commercially valuable medicinal plants that are or could be cultivated as understory component(s) in forests and tree plantations

Latin name	Common name	Plant type	Parts used	Medicinal use	Location
Aconitum heterophyllum	*'Atis'*	Tall herb	Rhizomes	Hysteria, throat diseases, astringent	Alpine and sub-alpine Himalayas
Amomum subulatum	Large cardamom	Perennial herb	Seeds	Stimulant, indigestion, vomiting, rectal diseases	Sub-Himalayan range, Nepal, Bhutan,
Amomum villosum	*'Saren'*	Perennial herb	Seeds	Gastric and digestive disorders	China
Caulophyllum thalictroides	Blue cohosh	Perennial herb	Roots	Gynecological problems, bronchitis	North America
Cimicifuga racemosa	Black cohosh	Perennial herb	Roots	Menses related problems	North America
Chlorophytum borivilianum	'Safed musli'	Annual herb	Tubers	Male impotency, general weakness	India
Costus speciosus	Crepe ginger	Cane	Leaves, stem, rhizomes	Purgative, depurative and as a tonic	India
Dioscorea deltoidea	Himalayan yam	Vine	Tubers	Source of saponins and steroids	India, Pakistan
Echinacea purpurea	Coneflower	Perennial herb	Roots, rhizomes	Enhancing immune system	North America
Hydrastis canadensis	Goldenseal	Perennial herb	Rhizomes	Tonic	North America
Panax ginseng	Ginseng	Herb	Roots	Tonic	China, Korea, Japan
Panax quinquefolium	American ginseng	Perennial herb	Root	Tonic	North America
Cephaelis ipecacuanha	Raicilla, Ipecac	Shrub	Roots	Whooping cough, bronchial asthma, amoebic dysentery	Brazil, India, Bangladesh, Indonesia
Rauvolfia serpentina	Rauvolfia	Shrub	Roots	Hypertension and certain forms of insanity	Sub-montane zone, India
Serenoa repens	Saw palmetto	Shrubby-palm	Fruits	Swelling of prostrate gland	Southeastern USA

Source: Rao et al. (2004)

attains exploitable tuber size in about 10 years. (Table 11.2)

Medicinal plants are an invariable component of homegardens, whether they are in the Peruvian Amazon (Lamont et al. 1999), on the slopes of the Mt. Kilimanjaro in Tanzania (O'Kting'ati et al. 1984), or in the humid and semiarid Cuba (Wezel and Bender 2003). The species composition differs depending on cultural background, distance from markets, and the influence of tourism. Medicinal plants accounted for about 27% of total plant species in the homegardens in Amazon (Padoch and de Jong 1991), 56% in northern Catalonia (Iberian Peninsula) (Agelet et al. 2000), and 45% in the floodplains of the river Jamuna in Bangladesh (Yoshino and Ando 1999). In the Soqotra Island, Yemen, endemic medicinal plants such as *Aloe perryi*, *Jatropha unicostata,* and *Commiphora ornifolia* are cultivated in homegardens (Ceccolini 2002). On St. Croix and St. Thomas, US Virgin Islands, the medicinal trees *neem* (*Azadirachta indica*), moringa (*Moringa oleifera*), and noni (*Morinda citrifolia*) have become popular in homegardens (Palada and Williams 2000). The integration of medicinal plants in agroforests and multistrata systems can be utilized to grow MAP species for home use besides those targeted to niche markets to secure a higher premium on the premise of better quality similar to those harvested from the wild. The forest-type environment of these systems facilitates the integration of species that generally grow in the forest and thereby helps conserve the endangered species and produce them for markets. Such high-value MAPs could be integrated with such newly established or existing agroforestry systems such as homegardens and multistrata systems that are recognized as remunerative, environmentally sound, and ecologically sustainable alternative land-use systems to slash-and-burn systems and "alang alang" (*Imperata cylindrica*)-infested degraded lands in humid tropics (Tomich et al. 1998).

Rao et al. (2004) identified various other opportunities for incorporating MAP in AFS, including:

- Medicinal plants (trees) such as *Parkia roxburghii* as overstory shade trees for coffee, cacao, and tea in India
- Medicinal trees at wide spacing over herbaceous MAPs; such shade trees include *Prunus africana*, *Eucalyptus globulus* (for oil), sandalwood (*Santalum album), ashok (Saraca indica*), wood apple or bael (*Aegle marmelos*), custard apple (*Anona squamosa*), *amla* (*Emblica officinalis*), drumstick or moringa (*Moringa oleifera*) and soap nut tree (*Sapindus mukorossi*)
- MAPs intercropped with fuelwood trees; e.g., *Acacia auriculiformis*, *Albizia lebbeck*, *Eucalyptus tereticornis*, *Gmelina arborea*, and *Leucaeana leucocephala* as shade trees in India over *safed musli* (*Chlorophytum borivilianum*), rauvolfia (*Rauvolfia serpentina*), turmeric (*Curcuma longa*), wild turmeric (*C. aromatica*), *Curculigo orchioides*, and ginger (*Zingiber officinale*) (Prajapati et al. 2003)
- The age-old practice of intercropping MAPs such as cardamom (*Elettaria cardamomum*) and *kacholam* or galangal (*Kaempferia galanga*), traditionally intercropped in mature stands of coconut (*Cocos nucifera*) and areca or betelnut (*Areca catechu*) in southern and southwestern parts of India (Kumar et al. 2005)
- Increasing interest in growing on alternative crops that have better economic potential than traditional crops in the Caribbean islands, e.g., for specialty crops such as the West Indian hot peppers (*Capsicum chinense*), thyme (*Thymus vulgaris*) and chives (*Allium schoenoprasum*) in association with the medicinal trees, noni and moringa in the US Virgin Islands (Crossman et al. 1999; Palada and Williams 2000)
- Aromatic grasses such as vetiver (*Vetiveria zizanioides*), lemongrass (*Cymbopogon citratus*), and citronella (*C. nardus*) grown on field bunds and soil conservation bunds in croplands in contour strips or as a live hedge barrier and to stabilize terrace risers on sloping lands in several countries, including India, Fiji, Haiti, and Indonesia (NRC 1993).

Agroforestry offers a convenient way of producing many MAPs in combination with traditional crops. Although the benefits and advantages of MAPs have long been recognized, the potential opportunities have not been fully explored, and sporadic promotional efforts by government agencies have, by and large, been inadequate. Serious research is needed on germplasm improvement of the priority species of MAPs, appropriate systems into which they can be integrated and their management, and value-adding processes. Existing government policies maybe not be conducive to the promotion of MAPs in many places. The potential of MAPs can be realized when policy constraints are removed, and efforts are made simultaneously to commercialize the products and explore markets for lesser-known species.

11.4 Agroforestry for Ecosystem Protection

The role of agroforestry systems in providing various ecosystem services is discussed in detail in separate chapters of the book including Chapters 17 (Biological nitrogen fixation), 18 (Soil conservation and control of land degradation), 20 (Carbon sequestration and climate-change mitigation), 21 (Biodiversity), and 22 (Other ecosystem services). These discussions are relevant to the relatively little-studied systems considered here as well.

11.5 Other Agroforestry-Related Land-Use Systems

As mentioned in Chapter 2, many land-use related terms and "buzzwords" were coined and some became quite popular during the latter part of the 1900s, often suffixing the word "forestry." Most of them were focused on the central theme of forestry for the benefit of and with the involvement of people. Prominent among them are Social Forestry, Farm Forestry, and Community Forestry. Distinctions among such terms are hazy, but an underlying theme of all of them is the involvement of (local) people in planting, managing, and utilizing trees on farmlands (farm forestry), community lands (community forests), and socially (publicly) accessible lands such as the sides of roads, railways, and canals (social forestry). The development of these activities coincided with that of agroforestry. The circumstances and factors that contributed to the development and interest in such activities were also the same as those for agroforestry: escalating rates of tropical deforestation and promoting the age-old practice of growing wood and food (trees and crops) together with the involvement of people and wherever ecologically feasible, as explained in Chapter 1. Indeed, these commonalities in the circumstances and the underlying concepts make it often difficult to distinguish between agroforestry and the various other people-involved forestry programs, except when warranted by administrative regulations of the implementing agencies. In addition to the above activities focused on the tropics, there are some denoted by terms such as Urban and Peri-Urban Forestry, Urban Food Forest, Permaculture, Trees Outside Forests, and Carbon Farming, and so on, that are of wider applications in the tropics as well as outside the tropics. Satoyama is another term for a somewhat related theme that is promoted primarily in Japan. The salient aspects of such forestry-and-tree-focused terms and concepts and their relevance to agroforestry are briefly explained in the ensuing section.

11.5.1 Social Forestry

Social Forestry is probably the most prominent among such forestry-related terminologies. It highlights a shift in emphasis on forestry in developing countries from timber-and-revenue-generation toward forestry for meeting the needs of the local people. The term was coined and promoted during the 1970s and 1980s to emphasize the social value and importance of forests to people: "*Forestry is not about trees, it is about people*" (Westoby 1987). It became a "movement" to increase awareness about the role of tropical forests in meeting the felt needs of the rural poor, and a change in the philosophy and approach to forestry was heralded in the 1980s. Major social forestry programs were launched in many developing countries with the support of international agencies such as the Food and Agriculture Organization of the United Nations (FAO) and the World Bank (FAO 1981; World Bank 1991, 2004) as well as multinational and bilateral agencies of some industrialized countries.

Social forestry is the management and protection of forests and afforestation on barren lands to help in the environmental, social, and rural development, as against the traditional forest management objective of securing revenue. Besides generating employment for the rural poor and improving their livelihood, it helps in poverty alleviation and improving food security. Additionally, the promotion of tree planting on non-forest land was considered important to increase the rapidly decreasing green cover in many developing nations. Because of the infusion of international donor-derived funds, afforestation under social forestry dominated the forestry sector programs in many developing countries in the last two decades of the 20th century. Such initiatives usually included the distribution of tree seedlings to the farmers for planting on their private lands either as block plantations, shelterbelts, or in agroforestry combinations;

decentralized nurseries (small private or community-run nurseries) to supply seedlings for the other components of the program; fuelwood and fodder plantations on community lands or government-revenue land to supply sustained alternate source of these products; roadsides (Figure 11.6), canal banks, as strip plantations beside railway lines for the benefit of the local communities; and reclamation of degraded areas (planting forage grasses on degraded forests and public lands, stabilizing sand-dunes, and protecting watersheds in eroding catchments). In the scenario of global climate change, such interventions also hold promise in climate change mitigation, besides conserving biodiversity and providing ecosystem services. However, much of the enthusiasm in promoting social forestry programs seems to have subsided in the government and international-funding and policy arena since the 1980s, when it used to be projected as a profound tool for ensuring the basic needs of the rural poor.

11.5.2 Farm Forestry

Farm Forestry refers to "forestry undertaken on farms," i.e., commercial tree planting on farmers' private lands as woodlots, shelterbelts, scattered trees, or boundary rows. Broadly, it refers to any trees on farmland that are managed to produce saleable products such as timber, oil, tannin, and charcoal or carbon credits. Several examples are shown from a few different places: Western Guatemala (Figure 11.7), the foothills of the Himalayas in India (Figure 11.8), and Nepal (Figure 11.9). Farm forestry is an older concept than social forestry: Ferguson's (1916) book *Farm Forestry* described it as a branch of general forestry, comprising the principles that applied to the management of farm woodlots. In FAO literature (FAO 1988), farm forestry also includes tree planting on wastelands and degraded forests, besides privately owned agricultural lands, and is now being used to cover the commercial management of native forest on farms as well. As

Figure 11.6 Planting rows of fuelwood- and fodder trees along roadsides, railway tracks, canal banks, and other "common" lands was a major activity of the Social Forestry program when it was launched in India and many other developing countries with international support during the 1980s. The picture shows one such social forestry planting in Tamil Nadu state, India. (Photo: PKR Nair)

Figure 11.7 Farm Forestry in Western Guatemala. (Photo: PKR Nair)

Figure 11.8 Farm Forestry/Community Forestry in the foothills of the Himalayas. (Photo: PKR Nair)

Figure 11.9 Farm Forestry/Community Forestry in Nepal. (Photo: ICRAF/World Agroforestry)

mentioned, the distinction between terms such as agroforestry, farm forestry, and community forestry is faint and they overlap considerably and are sometimes used even interchangeably. Historically, farm forestry had been practiced in both developing and advanced economies around the world. Examples include plantations of *Eucalyptus* spp. in Australia, *Pinus radiata* in New Zealand, various hardwood and coniferous species in Europe and North America, and an array of tropical hardwood species from the farms in Asia and Africa. While farm forestry is practiced all over the world, in Australia it is increasingly promoted as a national strategy aimed to deliver important benefits in terms of expanding opportunities for commercial wood production, assisting the transition to more sustainable agriculture, and promoting regional development (Race and Curtis 1997).

11.5.3 Community Forestry

Community Forestry denotes tree planting activities undertaken by a community on communal lands, or the so-called common lands and involving the local people directly in the process – either by growing trees themselves or by processing the tree products locally. FAO (1978) interprets community forestry as "any situation that intimately involves local people in forestry activity." Reviewing the community forestry initiatives by governments and donors and civil society during the previous 25 years, Arnold (2001) argued that it was "interpreted not as a separate form of forestry, but as part of the process whereby forestry is being refashioned in line with broader societal and economic changes." As mentioned earlier, the distinctions between community forestry and social forestry are faint; sometimes one is presented as a subset of the other. In any case, the principal objectives of community forestry are not too different from those of social forestry: production of food, fuel, fodder, and small timber, and environmental benefits such as aesthetics and micro-climatic modification. A distinction can, however, be drawn between community forestry and farm forestry, that the latter aims to promote commercial tree growing by individual farmers on their private lands, while community forestry is based on the use of communal lands. Although community forestry as a forest management paradigm was initially focused on developing countries, many developed nations are also at the forefront of implementing it (Mallik and Rahman 1994), although the contexts are different.

11.5.4 Urban Forestry and Urban Food Forestry

The term *urban forestry* is a specialized branch of forestry that has been promoted primarily in North America and Europe since the 1960s with the overall objective of "the cultivation and management of trees for their present and potential contributions to the physiological, sociological, and economic well-being of urban society" (Johnston 1996). Gerhold (2007) further elaborated that urban forestry does not deal only "with the city trees or with single tree management, but rather with the tree management in the entire area influenced by the urban population." The scope of urban forestry was thus expanded to include the proximal area of a city or urban area (*peri-urban forestry*). In the United States, particularly, urban forestry has developed into a national movement with a proliferation of green infrastructure programs: see Chapter 10 (Section 10.3.5; Figures 10.12, 10.13).

Urban forests are multifunctional socio-ecological landscapes. Consequently, the term urban forestry is sometimes used synonymously with community forestry. While in traditional forestry, trees are managed for timber harvests and to provide other goods and services, in urban forestry trees are cultivated mainly for their aesthetic and environmental qualities, to be "harvested" only when they die or become hazardous. A well-managed urban forest has numerous advantages, ranging from aesthetic, economic, and health benefits of various kinds to favorable social and psychological influences. According to McLain et al. (2012), gleaning and gathering in urban forest landscapes may offer opportunities for residents to "steward public natural resources and interact deeply with nature".

An extension of urban forestry is the concept of *urban food forestry* (UFF). According to Clark and Nicholas (2013), who proposed the term, UFF conjoins elements of urban agriculture, urban forestry, and agroforestry. They defined it as "the intentional and strategic use of woody perennial food-producing species in urban edible landscapes to improve the sustainability and resilience of urban communities." As the world has been experiencing unprecedented levels of urbanization in the past few decades – a trend that is expected to continue – food and nutritional security is emerging as one of the principal concerns in many cities. The unparalleled growth of urbanization has also amplified the market demand for fruit, timber, and a host of other products, which necessitates the conversion of the areas around cities into multifunctional agroforests. Woody Perennial Polycultures (WPP) that mimic multistrata agroforestry systems are common in the tropics and are being accepted as sustainable, ecologically-sound, land-use strategies in urban ecosystems. Developing such agroforestry practices in the urban and peri-urban remaining green spaces may enable combining the food production function with various ecosystem services, thus increasing the food and nutritional security for the urban poor and reconnecting the urban people to nature. Russo et al. (2017) observed that when implementing an edible green infrastructure (EGI) approach, which includes UFF, it can offer improved resilience and quality of life in cities and an EGI approach can contribute socially, economically, and environmentally to urban sustainability and food security.

11.5.5 Permaculture

Coined in the mid-1970s, the term permaculture (based on "permanent agriculture") refers to an "integrated, evolving system of perennial or self-perpetuating plant and animal species useful to man" (Mollison and Holmgren 1978). A more recent definition of permaculture with an expanded focus is "consciously designed landscapes which mimic the patterns and relationships found in nature while yielding an abundance of food, fiber, and energy for provision of local needs" (Holmgren 2002). Another characterization reads as "the conscious design and maintenance of agriculturally productive ecosystems, which have the diversity and resilience of natural ecosystems," the underlying philosophy being "caring for the Earth and its people." The promoters of the concept consider it a futuristic, ecologically-sound approach to providing for our needs, including food, shelter, and financial and social structures. The wide variety of plants ranging from large, overstory trees to herbs and climbers, creates habitat and food diversity allowing a complex set of fauna. Permaculture also implies the potential for the continuous evolution of vegetation toward a desirable "climax state" (succession). That is, the suite of perennial plants and animals evolve with the system and the ecosystem may move toward a climax. Although conceptually appealing, field-scale evidence for such long-term vegetation dynamics in permaculture systems is scanty.

11.5.6 Trees Outside Forests

The concept of *Trees outside Forests* (TOF) signifies trees growing outside the forest and not belonging to the forest or other wooded land (Bellefontaine et al. 2002). Similar to the several other new words with "forestry" endings that emerged in the late 1900s as mentioned earlier in this chapter, this expression also represents a loose conceptual framework with no clear definitions, and its scope varies from place to place, and may subsume some of the practices described in this chapter including social forestry, community forestry, and farm forestry. Thus, woodlots, gallery forests, and riparian buffers, scattered trees on farmland and pasture, or in linear and strip plantings along roads, canals, and watercourses, around lakes and water bodies, avenue trees, or trees in small spatially contiguous assemblages such as clumps of trees, sacred woods/groves, urban parks, and all such stands of trees are examples of TOF. Long and Nair (1999) included "agro-, community-, and urban forestry" under TOF. The FAO publication (de Foresta et al. 2013), containing several excellent photographs of various examples of TOF, describes that the term (TOF) represents an effort to concentrate attention that had been spread out on components of this rather diffuse resource: agroforestry, silvopastoralism, urban and rural forestry, and other related disciplines.

Boundary Planting is a term used commonly in various regions to denote linear plantings of trees around plot/field boundaries. They have both productive (e.g., orchards, trees in fields, and agroforestry systems) and protective (e.g., trees with an ecological or landscaping) functions, besides ornamental values (e.g., trees around houses, in parks, and towns). Two examples are presented in Figures 11.10 and 11.11.

Urban Homegardens, a variant of the tropical homegardens (Chapter 7) involving intimate, multispecies associations of different types of fruit trees and short-duration crops such as vegetables and other short-duration plants in small parcels of land around homes, are also now getting some attention in urban settings (Drescher et al. 2006); two examples are presented as Figures 11.12 (from the Philippines) and 11.13 (from Guangdong, China).

The trees outside forests contribute substantially to the national biomass and carbon stocks and the livelihoods of people (Schnell et al. 2015), besides being the only wood resources available to local people. The widely quoted Zomer et al. (2009, 2016) estimates that "globally there are about 10 million km^2 (or 46 % of the total agriculture land) with more than 10 % tree cover" perhaps represent the extent of the total global area under TOF. Indisputably, trees outside forests – irrespective of the terms by which they are known – have enormous social, cultural, and economic importance.

11.5.7 Carbon Farming

The term refers to a variety of farming methods organized around carbon sequestration in soils and plants. Toensmeier (2016), in his book *The Carbon Farming Solution,* describes how agroforestry

Figure 11.10 Trees Outside Forests - boundary planting: A boundary row of *Gliricidia sepium* around an agricultural field in Hawaii. (Photo: Craig Elevitch)

Figure 11.11 Trees Outside Forests - boundary planting: Another example of boundary planting of *Acacia mangium* around coffee fields in Hawaii. (Photo: Craig Elevitch)

Figure 11.12 An urban homegarden near Manila International Airport with a dense multispecies assemblage of various plants in the background. (Photo: AW Drescher)

Figure 11.13 The Guangdong village homegarden in Guandong, China: Mangoes, litchis, bananas, sweet potatoes, cabbage, and carrots. (Photo: Daniel M. Cartledge)

systems involving NDHP (non-destructively harvested perennial) species are excellent examples of carbon farming. The underlying principle is to exploit the photosynthetic ability of plants to capture and convert atmospheric carbon dioxide into carbohydrates (Chapter 12) and the carbon storage potential of soils to reduce the high and continually increasing levels of carbon dioxide and other greenhouse gases in the atmosphere. See Chapter 20 for a detailed explanation of the scientific principles involved.

11.5.8 Satoyama: The Socio-Ecological Production Landscape of Japan

Another land-use system, which has functional similarities to agroforestry, is the *Satoyama* system of Japan. Satoyama, combining the root words *sato* (=village) and *yama* (= hill or mountain) is a Japanese term originally used to refer to traditional agricultural woodlands (Shidei 2000). Descriptions, however, vary with disciplinary perspectives. While the foresters consider satoyama simply as a forested land with human settlements, those connected with agriculture consider it as rice paddy fields mixed with terraces or agricultural lands. The term has lately acquired and been used in a broader context as the "satoyama landscape" (Figures 11.14) signifying all remaining natural environments, or the entire landscape used for agricultural activity (Kumar and Takeuchi 2009; Ichikawa and Toth 2012). In that sense of the term, it represents a sequence of intimately linked agricultural land-use systems such as woodlands, farmlands, settlements, and reservoirs, bordered on the upper reaches by forests (man-made or natural). Upland terraces, lowland rice-paddies, ponds, grasslands, and wildlife habitats — often situated midway between mountains and flatlands — are integral to this mosaic, which constitute about 40% of the national lands of Japan (Takeuchi 2003). Ichikawa and Toth (2012) have reported that a notable decrease and abandonment of the

Figure 11.14 A satoyama landscape in Kumano, Japan. A rice (paddy) field and an adjacent terraced uplands with a woodlot in the background represent the mosaic structure of a conserved satoyama landscape Kumao, Japan. (Photo: Winifred Bird, with permission)

satoyama landscape during the rapid economic growth after World War II have ironically promoted gradual development of awareness and interest among the Japanese people about the value of the traditional systems. The growing awareness of the need for food safety and environmental conservation measures support the revitalization of the declining satoyama landscapes.

Satoyama is an excellent example of a socio-ecological and multifunctional production landscape consisting of many divergent habitat types, including rice paddies, secondary forests, secondary grasslands, ponds, and streams. High species diversity is a characteristic feature of these unique land-use systems (Kumar and Takeuchi 2009). These traditional rural landscapes are important culturally too and provide social and ecological networking to the village community (Moriyama 1998), just as the agroforestry homegardens of Java, Indonesia do (Somearwoto 1987). Similar systems exist also in other Asian countries such as China and Korea as well as the eastern parts of Russia.

Some global initiatives have been made to evaluate the dynamics of coupled natural and human systems and conserving them. Examples include the *Satoyama and Satoumi* (marine and coastal ecosystems with human interaction) *Ecosystems and Human Well-Being* initiative (2006–2010). The Satoyama Initiative (launched in 2010) is "a global effort to realize societies in harmony with nature" (http://satoyama-initiative.org/) as a partnership of the United Nations University Institute for the Advanced Study of Sustainability (UNU-IAS) and the Ministry of the Environment of Japan. It focuses on the revitalization and sustainable management of "socio-ecological production landscapes and seascapes" (SEPLS), where production aids in the maintenance of biodiversity and provision of ecosystem services on the one hand, and support livelihood security and well-being of local communities on a sustained basis, on the other. This was preceded by many domestic efforts in Japan, which focused on the conservation of different types of SEPLS around the world (of which, satoyama is one).

11.5.9 The Damar Agroforests of Indonesia

As noted in Chapter 7 (Section 7.7.2; Figure 7.10), Damar (*Shorea javanica*) agroforests of Sumatra and elsewhere in Indonesia is a variant of the homegarden system. The farmers have established these forest gardens by planting damar trees in upland swidden rice fields. The damar tree yields a resin, locally known as *damar mata kucing* in Sumatra. It is used in the production of incense, varnish, paint, and cosmetics. Traditionally, the resin used to be collected from the damar trees in the natural forests. However, as the wild resources were dwindling, attempts were made to establish damar gardens. Harvest of resin from damar trees constitutes the principal source of household cash income. The system also offers considerable scope for preserving high levels of biodiversity and provides a whole range of ecosystem services, which were originally derived from the forest.

11.6 Concluding Remarks

The chapter gives an overview of the diversity of the myriad of little-known and underexploited agroforestry systems that exist in different parts of the world, especially the tropics. These systems offer a variety of products ranging from food, animal feed, fuelwood, medicines, and numerous wood products as well as ecosystem services including the control of soil erosion and land degradation, climate change mitigation, biodiversity protection, cultural and social benefits. These time-tested systems that are intricately intertwined with the cultural and societal heritage of the practitioners and are repositories of a wealth of biological and social systems have unfortunately been ignored or bypassed by development agendas and efforts. A little effort into understanding and improving these systems will bring rich rewards and dividends.

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Section III

Biophysical Foundations of Agroforestry: Plant Productivity

General Principles of Plant Productivity 12

Contents

Abstract

This chapter briefly explains the fundamental processes that support plant production on Earth and clarifies the several terms and methods used for measuring and expressing plant productivity. Photosynthesis is the process by which green plants and some other organisms use sunlight (solar energy) to synthesize carbohydrates (chemical energy) from carbon dioxide (CO_2) and water. In most plants including all trees, CO_2 fixation, i.e., the formation of carbohydrate, follows the C3 cycle (reductive pentose phosphate cycle); but some warm-season grasses such as maize and sugarcane follow the C4 dicarboxylic acid cycle. Respiration refers to the process of breakdown (oxidation) of the sugars formed during photosynthesis to yield the energy required for plant growth. Photosynthesis results in increased dry weight due to CO_2 uptake, while respiration results in the release of CO_2, and therefore reduction of dry weight. Under optimal conditions, respiration accounts for about a 33% reduction of photosynthates. Plant productivity, i.e., the amount of growth that is attained by a plant within a given period, is a function of net photosynthesis, which is the difference between gross photosynthesis and respiration. Gross Primary Productivity (GPP) is the product of photosynthetic fixation of carbon, whereas Net Primary Productivity (NPP) refers to the carbon that is actually converted into biomass.

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Choice of appropriate species for specific locations and shade management through planting arrangements and plant management are the broad principles for manipulating photosynthesis and plant productivity in agroforestry systems. Judging from the experience of the Green Revolution, efforts in applying the principles of plant productivity to develop plants adapted to combined production systems such as agroforestry will be several times more demanding and challenging, but possibly rewarding too.

12.1 Introduction

In a biological sense, plant production can be viewed as a process of conversion of solar energy into biologically useful chemical energy that can be stored and transported. This conversion happens through a reaction called photosynthesis, which is the basis of plant production and the most important biochemical reaction on Earth. Through this process, green plants convert solar energy, carbon dioxide, and water to glucose and other carbon-based compounds and ultimately into plant tissues. The general principles underlying the photosynthetic process are quite well understood. Since these principles are so important in managing all plant production systems, we will review them – albeit briefly – to emphasize the importance of plant management for optimal exploitation of photosynthesis by different components of agroforestry systems. Several textbooks that describe the different aspects of photosynthesis are available; to mention a few: Govindjee et al. 2006; Eaton-Rye et al. 2012; Blankenship 2014; Taiz et al. 2014; Lambers and Oliveira 2019; Shevela et al. 2019. The information presented here has been synthesized from several such resources. But the readers are advised to refer to such basic textbooks on plant physiology for a better understanding or recapitulation of the subject. It also needs to be noted that although mathematical modeling of photosynthesis has been attempted in a big way to better understand the dynamics of this process (see reviews by Lazár and Schansker 2009; Jablonsky et al. 2011; Stirbet et al. 2014, 2019), such details are beyond the scope of this book.

12.2 Photosynthesis and Respiration: The Basics

Photosynthesis sustains nearly all forms of life on Earth. As mentioned above, it is the process of the conversion of a part of the solar energy into biologically useful chemical energy. The global equation of photosynthesis is as follows:

$$6CO_2 + 12H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Photosynthesis essentially is an oxidation-reduction reaction. Based on the nature of the electron donor involved, two variants are recognized in nature: *oxygenic* photosynthesis and *anoxygenic* photosynthesis. Photosynthesis by plants, algae, and cyanobacteria (or blue-green algae) is called oxygenic photosynthesis because one of its products is molecular oxygen (O_2), which arises from the oxidation of water (H_2O). Oxygenic photosynthesis encompasses the conversion of reactants such as water and CO_2 into carbohydrate and oxygen. It represents the most common form of photosynthesis where the initial electron donor is water, and, as a consequence, molecular oxygen is liberated as a byproduct. Bacterial photosynthesis other than that of cyanobacteria, however, does not result in the evolution of O_2 and hence is called anoxygenic photosynthesis, where alternate substances such as hydrogen sulfide (H_2S) are used as electron donors, instead of water. Oxygenic photosynthesis, hereafter referred to as *photosynthesis*, is the fundamental process of importance in all forms of plant production including food, fiber, and many other useful substances, and it supports almost all forms of life on Earth, either directly or indirectly.

Photosynthesis takes place in special cell organelles called chloroplasts. The ultrastructure of chloroplasts indicates two exterior membranes, which surround the *stroma* – the fluid-filled internal space of chloroplasts (Figure 12.1). A closed

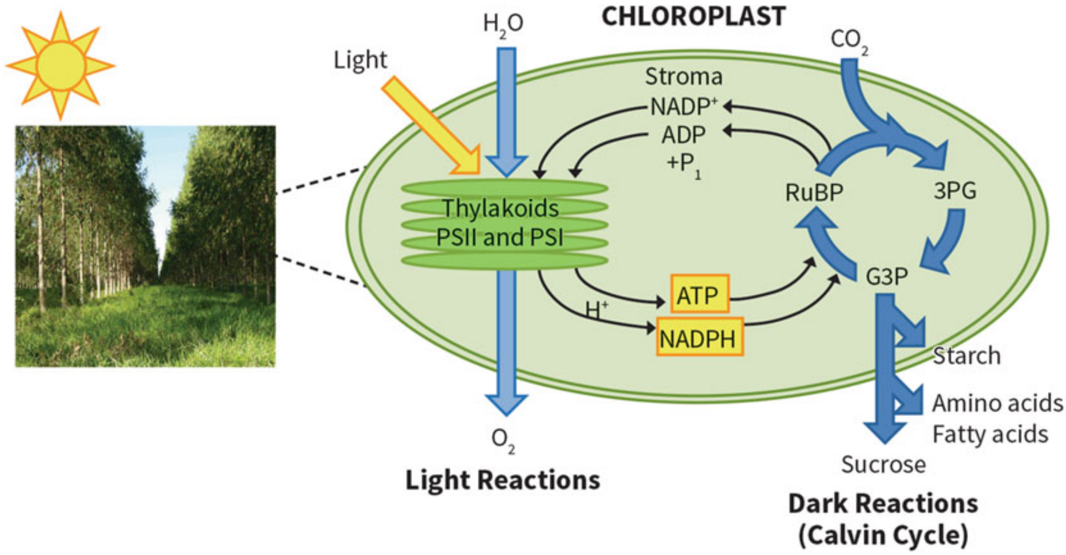

Figure 12.1 Diagrammatic representation of photosynthesis in the chloroplast of a leaf: the light reactions and dark reactions (carbon fixation) of photosynthesis. The light reactions occur in the thylakoid membrane (embedded in stroma) and the dark reactions take place in the stroma of the chloroplast. Photosystems I and II (PSI and PSII) are the two multi-protein complexes that contain the pigments necessary to harvest photons and use light energy to catalyze the primary photosynthetic endergonic reactions producing high energy compounds. Photosystem II precedes Photosystem I in the electron flow of photophosphorylation. Adapted from Rasmussen and Minteer (2014). © The Electrochemical Society. Reproduced by permission of IOP Publishing. All rights reserved

membrane vesicle, the *thylakoid*, which contains the *lumen* (the continuous aqueous phase enclosed by the thylakoid membrane) occurs inside the stroma. The stroma is the locus for CO_2 fixation in photosynthesis (the dark reactions, explained below) and the thylakoid membrane is the site for the conversion of light energy into the energy of the chemical bonds (light reactions). The photosynthetic process (light and dark reactions) resulting in the production of carbohydrates, including the sites for light and dark reactions, is explained in Figure 12.1.

The first step in photosynthesis is the absorption of solar (light) energy (i.e., photons of different wavelengths) by pigments enclosed in the so-called *antenna protein complexes*. The antenna complex is a light-harvesting membrane-associated aggregate of proteins and photosensitive pigments such as chlorophylls and carotenoids (in higher plants). Situated inside the chloroplasts of photosynthetic organisms, they capture light energy and transfer it in the form of excitation energy to the reaction centers (RCs) – a protein where photochemical reactions occur. The RCs are located in two large membrane-bound pigment-protein complexes: *photosystem I (PSI)* and *photosystem II (PSII)*. A photosystem consists of many light-harvesting complexes that form an antenna of hundreds of pigment molecules, which "funnel" (collect and concentrate) excitation energy and transfer it towards a "special pair" of chlorophyll molecules found at the core (RC) of the photosystems. The photosystems, PSI and PSII, are multi-protein complexes that contain the pigments necessary to harvest photons and use light energy to catalyze the primary photosynthetic reactions producing high-energy compounds.

Following the trapping of the excitation energy by special photoactive chlorophyll molecules in the RCs, light energy is converted into chemical energy, through primary photochemical reactions (Figure 12.1). This process starts in the thylakoid membrane with two light reactions taking place simultaneously at PSII and PSI reaction centers. This energy is used for propelling the redox chemistry of the "extraction" of electrons from water in a series of distinct stages and transmitting the same to $NADP^+$ (oxidized form of nicotinamide adenine dinucleotide phosphate). Additionally, water is oxidized to O_2, and $NADP^+$ is reduced to NADPH, besides producing ATP. The latter two (NADPH and ATP) are used in the dark reactions of photosynthesis (CO_2 assimilation), which take place in the stroma. Rubisco (ribulose 1,5-bisphosphate carboxylase/oxygenase) is the principal enzyme catalyzing the fixation of CO_2 on to RuBP (ribulose 1,5-bisphosphate, a five-carbon compound).

As explained, the photosynthetic process involves different reactions in the presence of light or with no direct contribution of light to the chemical reaction (usually called "light reactions" and "dark reactions," respectively; Figure 12.1). During the light reactions, water is split into oxygen, protons, and electrons using light, while the dark reactions employ the protons and electrons to reduce CO_2 to carbohydrate via the Calvin cycle or the C3 cycle (explained below), which consumes the ATP and NADPH produced during the light reactions. The dark reactions happen all the time not only in dark, while light reactions happen only with light. Despite the complexity of the dark reactions, the carbon fixation step (i.e., the formation of carbohydrate incorporating CO_2) is carried out by a single enzyme, Rubisco. The equations below summarize the light and dark reactions (carbohydrates represented by the general formula CH_2O):

Light reactions:

$$2H_2O + \text{light} \rightarrow O_2 + 4H^+ + 4e \left(\Delta G^o = +317\ \text{kJ mol}^{-1}\right)$$

Dark reactions:

$$CO_2 + 4H^+ + 4e^- \rightarrow CH_2O + H_2O \left(\Delta G^o = +162\ \text{kJ mol}^{-1}\right)$$

Overall reaction (summary):

$$H_2O + \text{light} + CO_2 \rightarrow CH_2O + O_2 \left(\Delta G^o = +479\ \text{kJ mol}^{-1}\right)$$

The positive free energy change (ΔG°) implies that it requires energy for the reaction to proceed, which is provided by the absorbed solar energy; such reactions where the net change in free energy is positive are called *endergonic* reactions. This energy is converted into the chemically bound energy of the products. By facilitating the conversion of solar energy into chemical energy, photosynthesis acts as the primary energy input into the global food chain.

Calvin cycle: Plants differ in biochemical pathways for CO_2 reduction. In most plants, CO_2 fixation follows the Calvin cycle or the C3 reductive pentose phosphate cycle. Also known as the Calvin-Benson cycle, it involves a series of redox reactions that take place in the stroma of the chloroplast. Broadly, there are three steps: Carbon fixation, Reduction, and Regeneration. In the first stage, **Carbon fixation**, a CO_2 molecule combines with a five-carbon acceptor molecule, RuBP, which is catalyzed by the enzyme Rubisco. It produces a six-carbon compound that splits into two molecules of a three-carbon compound, 3-phosphoglyceric acid (3-PGA). In the second stage called **Reduction**, ATP and NADPH are used to convert the 3-PGA molecules into molecules of a three-carbon sugar, glyceraldehyde-3-phosphate (G3P). In this step, NADPH is the electron donor, and the reduction results in the production of a three-carbon intermediate to make G3P, through a two-step process: first, each molecule of 3-PGA receives a phosphate group from ATP, turning it into a doubly phosphorylated molecule called 1,3-bisphosphoglycerate (and leaving behind ADP as a by-product). Second, the 1,3-bisphosphoglycerate molecules are reduced (gain electrons). Each molecule receives two electrons from NADPH and loses one of its phosphate groups, turning it into a three-carbon sugar, G3P or its isomer, dihydroxy acetone phosphate (DHAP). Finally, in the **Regeneration stage,** some G3P molecules go to make glucose, while others are recycled to regenerate the RuBP acceptor. Regeneration requires ATP and involves a complex network of reactions.

During the past 40 million years or so when the Calvin cycle remained the predominant photosynthetic pathway, the Earth's climate system has changed and the atmospheric CO_2 levels declined (Huber and Caballero 2011), except of course in the recent past. Consequently, during the evolutionary process, some plants have evolved novel photosynthetic pathways to compensate for deficiencies in the preexisting C3 pathway. The C4 and Crassulacean Acid Metabolism (CAM) photosynthetic systems (Sage et al. 2012), which are essentially CO_2-concentrating mechanisms (CCMs), are prominent examples of this. The CCMs aim to increase the concentration of CO_2 relative to O_2 in the vicinity of Rubisco.

The C4 pathway: MD Hatch and CR Slack discovered in the 1960s that certain plants rescue CO_2 differently from the C3 pathway, according to a C4 dicarboxylic acid cycle (Figure 12.2). The C4 photosynthesis – found mainly in plants of the warm season grasses (family: Poaceae or Gramineae) such as maize (*Zea mays*), sugarcane (*Saccharum officinarum*), and savanna grasses – is indeed an important CCM, as mentioned. Such plants are called C4 plants and involve the enzyme phospho*enol*pyruvate (PEP) carboxylase as a CCM that aims to increase the concentration of CO_2 relative to O_2 in the vicinity of Rubisco. In C4 plants, light and dark reactions are spatially separated. The C4 plants also show specialized leaf anatomy called Kranz anatomy. Kranz, the German word for the wreath, refers to a bundle sheath of cells that surrounds the central vein within the leaf, which, in turn, are surrounded by the mesophyll cells. The mesophyll cells in such leaves are rich in the enzyme PEP carboxylase, which fixes CO_2 into a 4-C carboxylic acid, oxaloacetate. The oxaloacetate formed by the

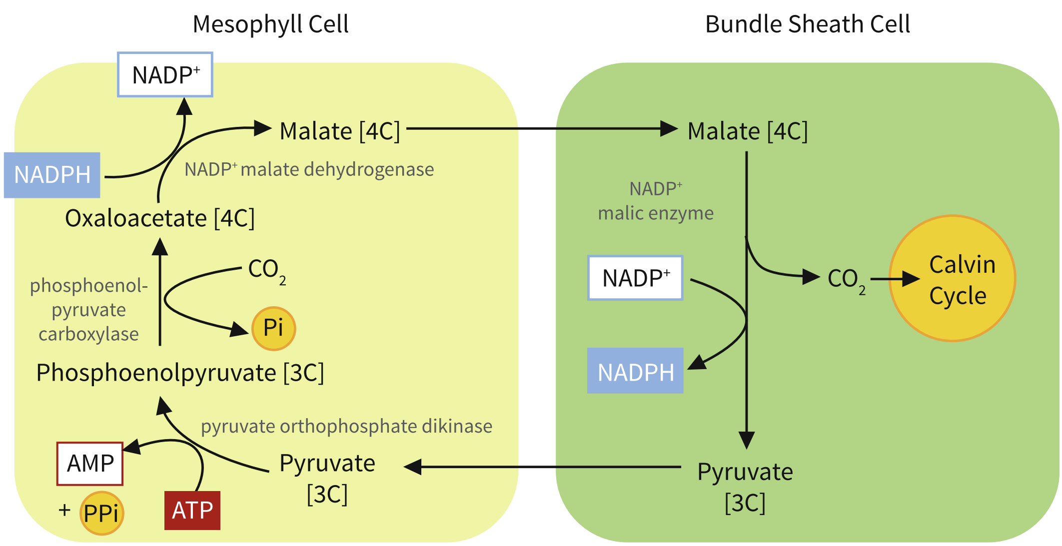

Figure 12.2 The C_4 pathway ($NADP^+$–malic enzyme type) for fixation of CO_2. Note that a distinctive feature of the C_4 plants is the bundle sheath cells (Kranz anatomy). The mesophyll cells surrounding the bundle sheath are rich in phosphoenolpyruvate carboxylase that fixes CO_2 into oxaloacetate. The oxaloacetate is reduced to malate, which is then exported to the bundle sheath cells, where it is decarboxylated to pyruvate, regenerating NADPH and CO_2. The CO_2 is then utilized by Rubisco in the Calvin cycle and the pyruvate is in turn returned to the mesophyll cells. Adapted from Johnson (2016). Reproduced by permission of the author

mesophyll cells is reduced using NADPH to another 4-C acid, malate. The malate is then exported from the mesophyll cells to the bundle sheath cells, where it is decarboxylated to pyruvate, thus regenerating NADPH and CO_2. The CO_2 is then utilized by Rubisco in the Calvin cycle. The pyruvate is, in turn, returned to the mesophyll cells where it is phosphorylated using ATP to regenerate PEP.

Photorespiration: The term refers to the light-dependent uptake of O_2 and the associated release of CO_2. Photorespiration is a physiological "malady" caused by the "malfunctioning" of the primary photosynthetic enzyme, Rubisco, in the so-called C3 or Calvin plants, where G3P is the stable end-product of the photosynthetic process. What initiates photorespiration is the oxygenation of RuBP by Rubisco, yielding 3-phosphoglycerate and 2-phosphoglycolate. The latter is produced when oxygen substitutes for CO_2 in the first reaction of photosynthetic carbon fixation and it is a compound with no known use in plant metabolism. Indeed, photorespiration results from a wasteful fixation of O_2 to produce 2-phosphoglycolate. Therefore, the efficiency of the C3 pathway is reduced when radiation and air temperature are high (Ehleringer et al. 1991). The C4 pathway, in particular, is a mechanism to counter photorespiration. Approximately 75% of the carbon entering 2-phosphoglycolate is recycled to 3-phosphoglycerate through a complex series of reactions, known as the "photorespiratory pathway" or the C2 cycle (Berry et al. 1978; Foyer and Noctor 2000). Lack of photorespiration is a distinct advantage of the C4 cycle, making C4 plants better suited to high irradiance (Figure 12.3). However, they are less adapted to shade than C3 species, which can alter leaf morphology and anatomy to harvest more light energy under shade. Therefore, the net photosynthesis of C3 plants is less reduced under low irradiance levels (or, shade conditions) than in C4 plants (Figure 12.3 and Section 12.4.1).

CAM (Crassulacean Acid Metabolism): is another mode of photosynthesis in a few plants including pineapple (*Ananas comosus*), and some desert species such as agave (*Agave* spp.) and cactus (*Opuntia* spp.). It is characterized by nocturnal stomatal opening; CO_2 uptake and fixation by PEP carboxylase (PEPC) in the cytosol (the aqueous component of the cytoplasm of a cell); and transition from PEPC to Rubisco-mediated carboxylation during the early light period leading to carbohydrate production. The CAM plants keep their stomata closed during the hot day times and open them in the cool of the night, and the CO_2 absorbed through the leaf openings is stored in organic acids (e.g., maleic acid). This delayed photosynthesis greatly reduces water loss during the day thereby enhancing the succulent plant's ability to maintain favorable water balance/improved water use efficiency. The dark and light reactions are separated temporally, with light reactions happening during the day and dark reactions happening at night.

Plant Respiration (Aerobic respiration): Also known as **Dark Respiration** (in contrast to photorespiration described under the C4 pathway) and **Mitochondrial Respiration** (because the process requires oxygen and occurs in organelles called mitochondria), it refers to the process of breakdown (oxidation) of the sugars formed during photosynthesis to yield the energy required for plant growth. In many ways, this is the inverse of photosynthesis. Plant physiology textbooks (e.g., Pallardy 2007; Chapin III et al. 2012; Taiz et al. 2014; Lambers and Oliveira 2019) provide detailed accounts on the respiration of plants. Therefore, as in the case of other basic mechanisms mentioned in this chapter, only some most salient aspects are mentioned here.

Common to all eukaryotes (i.e., organisms whose cells have a nucleus enclosed within a membrane), aerobic respiration is a process by which the carbohydrates are oxidized into H_2O and CO_2 with the release of energy.

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \left(\Delta G^o = -479 \text{ kJ mol}^{-1}\right)$$

Contrary to photosynthesis, aerobic respiration is an *exergonic process* (negative ΔG^o). The

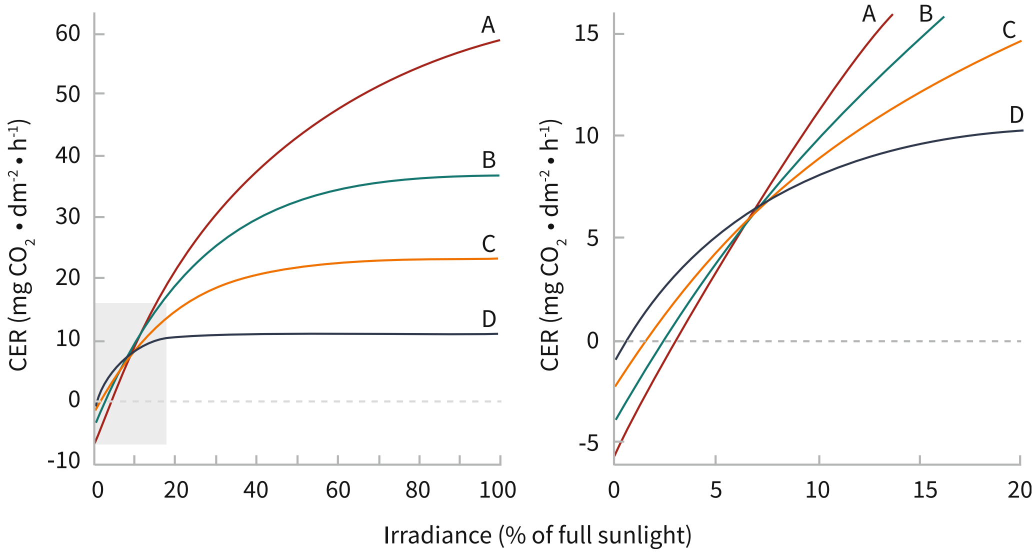

Figure 12.3 General patterns of light-response curves for C_3 and C_4 plants. The light compensation point (crossover with the dotted black line) is the irradiance level at which CO_2 uptake due to photosynthesis is equal to CO_2 evolution due to dark respiration. Light compensation point, the photosynthetic efficiency (slope at light limiting conditions), and the light saturation point (inflection points of the curves) are higher for C_4 plants than C_3 plants. The light saturation level is an irradiance level at which an irradiance increase would not result in a significant increase in the carbon exchange rate (CER). Light intensities left of the light saturation point are light-limited and right of it are CO_2 limited. The C3 species use dimmer light more efficiently than C4 plants. The figure on the right is an enlargement of the low light level responses (shaded areas of the graph on the left). The letters represent the following species: (A) C_4 species, e.g., corn (*Zea mays*), sorghum (*Sorghum bicolor*), sugarcane (*Saccharum officinarum)*, Bermuda grass (*Cynodon dactylon*); (B) Efficient C_3 sun species, e.g., soybean (*Glycine max*), cotton (*Gossypium hirsutum*), alfalfa (*Medicago sativa*); (C) Less efficient C_3 sun plants, e.g., tobacco (*Nicotiana tabacum*), red clover (*Trifolium pratense)*, orchard grass (*Dactylis glomerata*); and (D) C_3 shade species (e.g., include shade-adapted hardwood species, house plants). Adapted from Gardner et al. (1985). Republished with permission of John Wiley & Sons – Books

energy that is released is used by the organism for the numerous biosynthetic processes that facilitate growth and reproduction. Much of the energy and carbon skeletons necessary for biosynthesis and cellular maintenance are thus derived from respiration (Anaerobic respiration by prokaryotes, like bacteria that have no membrane-bound organelles, is excluded from this discussion).

Glycolysis: The oxidation of glucose (or other storage carbohydrates) to release energy through respiration involves a multi-step process. The first step is glycolysis (or, in the alternate, the oxidative pentose phosphate pathway), which involves the partial oxidation of glucose via phospho*enol*-pyruvate (PEP) into malate and pyruvate. Principal enzymes in glycolysis are regulated by adenylates (collective term for adenosine monophosphate or AMP, adenosine diphosphate or ADP, and adenosine triphosphate or ATP), in such a way as to speed up the rate of glycolysis when the demand for metabolic energy (ATP) increases. Unlike glycolysis, which is predominantly involved in the breakdown of sugars and the production of ATP, the ***oxidative pentose phosphate pathway*** (also known as the ***hexose monophosphate shunt***), is an alternative pathway to glycolysis, which generates NADPH and pentoses (5-carbon sugars), as well as a precursor (ribose 5-phosphate) for the synthesis of nucleotides.

Tricarboxylic Acid Cycle (TCA): Known also as the citric acid cycle or the Kreb's cycle, TCA is the second stage of respiration, when the malate and pyruvate formed during glycolysis in the cytosol are transported to the mitochondria, where it undergoes oxidative decarboxylation through a complex set of reactions. Complete oxidation of one molecule of malate yields four molecules of CO_2, five molecules of NADH, and one molecule of FADH2 (reduced flavin adenine dinucleotide), as well as one molecule of ATP.

Mitochondrial (dark) respiration has a profound impact on net ecosystem CO_2 exchange and the concentration of CO_2 in the atmosphere, and is, understandably, a major area of past and current research in plant productivity and ecosystem health and sustainability as reviewed by Atkin et al. (2005).

12.3 Plant and Ecosystem Productivity

12.3.1 Plant Productivity

Photosynthesis and respiration are, in many ways, similar but opposing reactions. Respiration uses energy from photosynthesis. Photosynthesis results in increased dry weight due to CO_2 uptake, while respiration results in the release of CO_2, and therefore reduction of dry weight. The simple carbohydrates formed by photosynthesis are transformed through respiration into the structural, storage, and metabolic substances required for plant growth and development. The ATP from the respiratory pathway is used for the synthesis of these substances. Under optimal conditions, respiration accounts for about a 33% loss or reduction of photosynthates.

The rate at which radiant energy is converted by the photosynthetic activity of producer organisms to organic substances is known as *primary, basic,* or *biological productivity* (Table 12.1). The keyword in this definition is the *rate*, i.e., the amount of energy fixed in a given duration of time. Biological productivity thus differs from "*yield*" (explained later), which implies that the reaction ends with the production of a given amount of material. In biological communities, the process is continuous in time, so a time unit must be designated, e.g., the amount of food manufactured per day or per year. Standing biomass or standing crops present at any given time should not be confused with productivity, because productivity in this context refers to the "rate of production."

Two variants of primary productivity are recognized (Table 12.1): **Gross Primary Productivity** (**GPP**) and **Net Primary Productivity** (**NPP**). While **GPP** is the product of photosynthetic fixation of carbon, **NPP** is the carbon that is actually converted into biomass. Plant productivity, i.e., the amount of growth that is attained by a plant within a given period, is a function of the net rate of photosynthesis (P_N), which is the difference between gross photosynthesis (P_G) and respiration (R):

$$P_N = P_G - R$$

Terrestrial GPP varies greatly over time and space. Variability in GPP is driven by a broad range of biotic and abiotic factors operating

Table 12.1 Common terms associated with plant productivity

Term	Description
Primary productivity	The rate at which energy is stored in the organic matter of plants per unit area of the earth's surface. It is often expressed in units of dry matter (e.g., grams of dry mass m^{-2} $year^{-1}$) rather than energy because of the ease of determining mass and the relative constancy of the conversion from mass to energy (caloric) units for plant tissues.
Gross primary productivity (GPP)	The amount of energy fixed (or organic material created) by plants in photosynthesis per unit of ground area per unit of time. However, plants use a considerable amount of the organic matter that they produce to meet their own respiratory demands.
Net primary productivity (NPP)	The amount of organic matter that is left after respiration.

mainly through changes in vegetation phenology and physiological processes.

12.3.2 Ecosystems and Their Productivity

An ecosystem refers to *the organisms and the non-living environment with which they interact* as a whole unit in its entirety rather than in terms of its various components and compartments. Consequent to the recognition of the enormous importance of the benefits derived from the ecosystems, the term *Ecosystem Services* became popular in both scientific literature and common parlance. In simple terms, ecosystem services are *the benefits that people obtain from ecosystems.* The major ecosystem services of agroforestry systems are discussed in detail in Chapters 19–22.

The distribution and descriptions of the ecosystems of the world at different levels of detail are available in numerous resources; a summary of the global distribution of the major ecosystems is presented in Figure 12.4. Productivity is among the most fundamental attributes of an ecosystem. The rate of biomass formation, i.e., NPP, which influences biological diversity and ecosystem dynamics, is closely linked to the potential to provide various ecosystem goods and services. In many ecosystems, the entire productive output (such as food and fiber, timber for wood products and paper, and forage for livestock) is harvested by humans and used for the support and maintenance functions (provisioning ecosystem services). Haberl et al. (2007) estimated that humans harvest nearly a quarter of the global NPP.

The elements that go into determining NPP are varied, and the appraisal schemes for each of these elements are complex. Extensive field surveys were conducted during the 1960s and 1970s under the aegis of the International Biological Programme to estimate terrestrial NPP (Ito 2011). Gough (2011) compiled the global and ecosystem-scale estimates of mean terrestrial gross and net primary production of the Earth's major biomes using remotely sensed satellite data and the results of modeling studies (Table 12.2). His global estimates of terrestrial NPP ranged from 48.0 to 69.0 Pg C yr^{-1} (1 Pg = 10^{15} g), and GPP (global terrestrial) as 121.7 Pg C yr^{-1}. The global distribution of terrestrial NPP estimated from spectral data gathered by

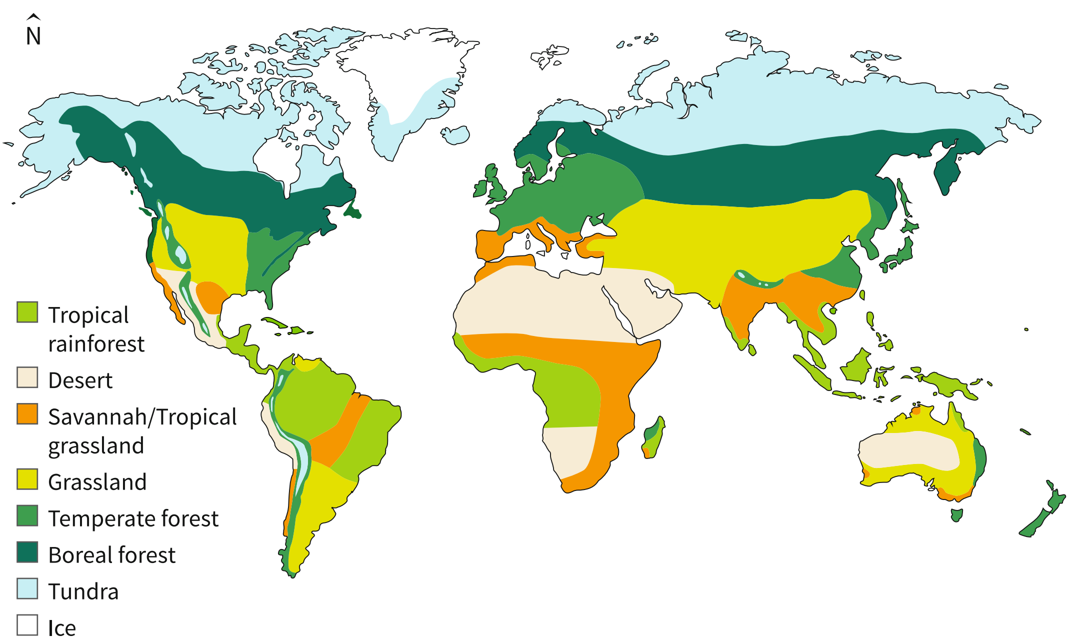

Figure 12.4 Distribution of major ecosystems around the world.
Source: https://lis488mapletrees.weebly.com/uploads/5/6/6/8/56680843/4229706_orig.gif

Table 12.2 Global and ecosystem-scale estimates of mean terrestrial gross and net primary production for the Earth's major biomes from remotely sensed satellite data and modeling studies [1 Petagram (Pg) = 10^{15} grams (g)]

Biome	Global GPP (Pg C year^{-1})	Global NPP (Pg C year^{-1})	Ecosystem NPP (g C ha^{-1} year^{-1})
Tropical forest	40.8	16.0–23.1	871–1098
Temperate forest	9.9	4.6–9.1	465–741
Boreal forest	8.3	2.6–4.6	173–238
Tropical savannah and grasslands	31.3	14.9–19.2	343–393
Temperate grasslands and shrublands	8.5	3.4–7.0	129–342
Deserts	6.4	0.5–3.5	28–151
Tundra	1.6	0.5–1.0	80–130
Croplands	14.8	4.1–8.0	288–468
Total	121.7	48.0–69.0	2377–3561

GPP = gross primary production, NPP = net primary production
Source: Compiled by Gough (2011)

NASA's satellite at various times are available at https://earthobservatory.nasa.gov/global-maps/MOD17A2_M_PSN. For November 2016, the values (g m^{-2} day^{-1}) ranged from near 0 (zero) in polar regions to 6.5 for tropical forest regions.

Tropical ecosystems account for nearly half of global NPP and GPP. Tropical forest ecosystems have substantially higher primary productivity levels compared to other terrestrial ecosystems such as temperate forests, tropical savannah, croplands, and boreal forests (Table 12.2). Temperate ecosystems and croplands account for roughly a quarter of global NPP and GPP. Productivity, thus, varies profoundly across the surface of the Earth and among different biomes. Terrestrial NPP varies latitudinally (north to south) and longitudinally (east to west) due to gradients in plant community composition, length of growing seasons, precipitation, temperature, and solar radiation. In general, NPP declines from Equatorial areas to the Polar Regions owing to altered light and temperature regimes. Tropical forests are among the most productive ecosystems on Earth and have a huge footprint on the Earth's surface. Desert and Tundra Biomes represent the least productive ecosystems, a reflection of their extreme precipitation and temperature regimes, respectively. Besides the climatic control of land-based primary production, factors such as disturbance regimes, ecosystem management, and land-use changes also exert profound influences on the spatial dissimilarities in terrestrial primary production (Gough 2011). Estimates of primary production also fluctuate temporally. The seasonality of biotic and abiotic factors are the key determinants of such temporal changes in productivity. In mid-latitudes, productivity values peak during summer.

12.3.3 Productivity Measurements and Evaluation in Agroecosystems

An agroecosystem is a subset of a conventional ecosystem and is arbitrarily defined as "a spatially and functionally coherent unit of agricultural activity and includes the living and nonliving components involved in that unit as well as their interactions." Simply stated, an agroecosystem includes the organisms and the environment of an agricultural area.

In agroecosystems represented by experimental plots and fields, ***Growth Analysis*** is a classical approach and a popular analytical tool for evaluating plant productivity. The terms and expressions used frequently in growth analysis (summarized in Table 12.3) include:

Relative Growth Rate **(RGR)** is one of the classical approaches in growth analysis indicating the proportionate growth of plant independent of their size. RGR expresses the dry weight increase in time interval in relation to the initial weight.

Table 12.3 Frequently used terms (growth parameters) in growth analysis

Term	Description	Unit
Relative Growth Rate (RGR)	The rate of accumulation of new dry mass per unit of existing dry mass	g g^{-1} day^{-1}
Leaf Area Index (LAI)	The ratio of the leaf area (one side only) of the plant to the ground area	m^2 m^{-2} (or unit-less being an index)
Crop Growth Rate (CGR)	Dry matter accumulation per unit of land area per unit of time	g m^{-2} (land area) day^{-1}
Net Assimilation Rate (NAR)	dry matter accumulation per unit of leaf area per unit of time	as g m^{-2} (leaf area) day^{-1}
Average Growth Rate (AGR)	Rate of increase in dry matter; indicates the growth of plants	g day^{-1}

Leaf Area Index **(LAI)** is the proportion of ground area covered by leaves.

Crop Growth Rate **(CGR)** is the gain in dry matter production on a unit of land in a unit of time. It is a measure of the productivity of crop plants (canopies).

Average Growth Rate **(AGR)** is an indicator of plant growth. It is defined as increase in dry weight per unit time. The calculation of average growth rate assumes a linear increase in plant growth.

Net Assimilation Rate **(NAR)** is a function of leaf surface area or the primary photosynthetic organs, and an indicator of the assimilatory capacity of plants.

[Given that NAR is a measure of the average net CO_2 exchange rate per unit of leaf area in the plant canopy, NAR x LAI = CGR.]

Land Equivalent Ratio (LER) is another method of productivity assessment that is used by agronomists (see Chapter 14, Section 14.4.3).

Biomass, Dry Matter, and Yield are terms that are commonly used (and sometimes misused) in land-use systems, ecology, and energy/environmental discussions.

Biomass refers to the mass of living biological organisms in an area or ecosystem at a given time. Biomass can refer to species biomass, which is the mass of one or more species, or to community biomass, which is the mass of all species in the community. It can include microorganisms, plants, or animals. The mass can be expressed as the average mass per unit area, or as the total mass in the community. Biomass includes both the above- and belowground plant parts such as leaves, twigs, branches, boles, as well as roots and rhizomes.

Dry Matter refers to what remains of a substance (e.g., a plant material) if all its water content is removed. For example, when a sample of leaves is dried in an oven at a constant temperature of about 75º C until a constant weight is obtained (mostly in about 60 hours), what remains is the dry matter. It represents the NPP and mineral content. The latter constitutes about 8% of the total dry matter and includes all the essential elements in the plant biomass except carbon (C), hydrogen (H), and oxygen (O) – see Chapter 15, Section 15.6 for details of essential elements and nutrients.

Yield (in plant production terminology) refers to the produce or product obtained from an agricultural or other land-use activity. It is expressed in mass per unit area of land in a defined timeframe (e.g., kg ha^{-1} $year^{-1}$); the time factor may vary depending on the species or operation (e.g., per crop, per harvest cycle in the case of frequently harvested products, rotation cycle in the case of tree plantations, and so on). The yield is usually expressed in terms of mass or volume measures of the marketable products and other commodities (e.g., cubic meters of wood). Dry matter is the yield parameter used in ecosystem measurements (NPP). A major difference between dry matter and commodity yields is the moisture content of the product: dry matter is devoid of moisture, whereas yields of grains and other commodities are expressed at the "standard" moisture levels prescribed for each commodity (< 12% for most grains).

12.4 Manipulation of Photosynthesis in Agroforestry

In agroforestry systems, the choice of component species and manipulation of shade through canopy management and planting configuration of the overstory species are the two principal factors that determine the photosynthetic efficiency – and, therefore, productivity – of the whole system.

12.4.1 Choice of Species

Although the choice of species for both the overstory and the understory components is important, the emphasis here is on the understory species. The overstory species, being of much longer duration than the understory, is often chosen with a longer-term perspective, and once established, they cannot be changed in the short term. On the other hand, there is more flexibility in the choice and management of the understory species that are seasonal or short-lived perennials.

The major factor that determines the performance of an understory component is its ability to tolerate shade, provided that the other growth factors such as temperature, water, and nutrients are not limiting. There is a long tradition of skillful selection and management of several such shade-tolerant species as understory crops in numerous traditional systems, especially the tropical homegardens (Chapter 7) and various lesser-known systems identified as "Cinderella agroforestry systems" (Nair et al. 2017: Chapter 11, Section 11.2). They maintain positive net photosynthesis even when the understory irradiance is relatively low. Cacao (*Theobroma cacao*), cardamom (*Elettaria cardamomum*), coffee (*Coffea* spp.), colocasia or taro (*Colocasia esculenta*), ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), yams (*Dioscorea* spp.), and many medicinal and aromatic plants are well-known examples of such shade-loving/tolerant tropical crops. In the temperate regions too, the Forest Farming practice (Chapter 10, Section 10.3.5) involves the cultivation of ginseng (*Panax* spp.) and several such shade-tolerant species under forest tree stands (Table 10.4). Several photographs included in Chapters 7 (homegardens), 8 (shaded perennial systems), and 11 (other agroforestry systems), show examples of shade-tolerant/adaptable plants of different forms (herbaceous annual/perennial, perennial climber, short tree species), including a few high-value commercial crops grown in agroforestry systems.

Shade tolerance is a function of plant ontogeny and many biotic and abiotic factors. Agroforestry practitioners around the world have a clear understanding of the shade adaptability and niche-compatibility – or, phenotypic plasticity – of the species and cultivars they grow in agroforestry combinations. Although arbitrary groupings of understory species as "shade sensitive," "shade-intolerant," "shade tolerant," and "shade-loving" can be found in agroforestry literature, these are mostly location-specific and are not based on quantitative and comparable criteria. Moreover, varietal and cultivar differences in shade adaptability are abundant within a species. Phenotypic plasticity generally tends to be low in shade-tolerant species (e.g., scant elongation in low light), but plasticity for certain traits, particularly for morphological features optimizing light capture, can be substantial (Valladares and Niinemets 2008). Serious studies on the nature, mechanisms, inheritance, and management of shade adaptability of understory species in agroforestry systems are highly warranted. From the management perspective of the components of agroforestry systems, there are opportunities for growing sun-loving (shade-intolerant) species when the tree component involved in the system is deciduous. For example, in the subtropical climates of the Indo-Gangetic plains of India, full-sun-demanding cereal crops such as wheat (*Triticum aestivum*) are cultivated as understory crops in plantations of deciduous poplar trees (*Populus* sp.) during the winter (locally known as *rabi*) season when trees are leafless (Figure 12.5). During the hotter rainy (locally known as *kharif*) season, warm/hot-season crops such as rice are grown as the understory species (Figure 12.6); multistrata systems involving fruit-trees in association with shade-tolerant annuals crops such as turmeric (*Curcuma longa*) are also commonly grown in association with *Populus* sp. by enterprising farmers (Figure 12.7). Since farmers have traditionally been selecting tree components based on their cultural and economic values and certain ecological factors, examples of shade-tolerant species abound in the farmers' fields (see Chapter 13, Appendix II), but no serious scientific effort has been undertaken to study the mechanisms of shade tolerance/adaptability of such species.

Thoughtful application of the general principles of plant productivity concerning their

Figure 12.5 Wheat under *Populus* sp. during the cool (*rabi*) season in subtropical Uttarkhand, India. (Photo: PKR Nair)

Figure 12.6 Rice under *Populus* sp. during the warm (hot) rainy (*kharif*) season in Uttarkhand, India. (Photo: ICRAF/World Agroforestry)

Figure 12.7 A multistory combination of turmeric (*Curcuma longa*), a shade-tolerant crop, in the understory (in the foreground) of a mixed stand of poplar (*Populus* sp.) the slender trees in the center) and mango (*Mangifera indica*) trees (lopped) in Yamunanagar, Haryana, India. (Photo: BM Kumar)

photosynthetic pathways will be useful for optimizing productivity in agroforestry. For example, under sound agronomic management in the tropics and subtropics, C4 monoculture systems should be more productive than C3 monoculture systems (Monteith 1978). This may be significant in agroforestry systems where annual or seasonal canopy types are important (as in hedgerow intercropping). For the annual or seasonal crops, it is imperative to build up leaf area as quickly as possible; C4 plants are the best candidates for this purpose. In conditions with a permanent woody overstory, the options are limited. Trees generally possess the C3 pathway; thus, the overstory will be C3. If shading caused by the overstory is significant, the C3 plants may be preferred as understory components as they have a greater efficiency of CO_2 uptake at lower irradiance levels than C4 plants (Figure 12.3). Conversely, if the overstory allows more light transmission to the understory, C4 types could as well be used as understory components. Understanding the distinct photosynthetic pathways of different species and the underlying physiological principles will undoubtedly be an important consideration in the search for "new" species and screening of local species for their agroforestry potential. Although the prevailing paradigm on sub-canopy (i.e., the canopy in the lower strata or tiers in a multi-strata configuration) photosynthesis is that shade trees strongly affect the physiology of the sub-canopy crops, the reduction in absorbed PAR, to a certain extent, can be compensated by an increase in light-use efficiency, which, in turn, may offset the difference in NPP between shaded and non-shaded plants. For example, Charbonnier et al. (2017) found that the NPP of shaded coffee (*Coffea* spp.) plants was "fairly stable" as light-use efficiency increased by 50%, regardless of a 60% reduction in sub-canopy irradiance.

The other major environmental factors that affect photosynthetic rates are temperature and the soil moisture- and nutrient-regimes. Agroforestry combinations and their interactions can cause considerable modifications in the availability of these growth factors as discussed in Chapter 14; however, under practical (field) conditions, the extent to which such fluctuations can cause significant effects on photosynthetic rates depends on site- and species-specific conditions. Screening crop varieties for their specific responses and understanding the mechanisms of the responses and manipulating them through easy-to-adopt management practices will be challenging areas for future research in agroforestry.

12.4.2 Shade Management

The major management options for manipulating photosynthesis of plant communities in agroforestry systems are based on the manipulation of the light (radiation) profile. For a plant community to use solar radiation effectively, the green, photosynthetic tissues must absorb most of the radiation. While the selection of species and their arrangement and management determine the photosynthetic efficiency of the whole plant community, the angle, disposition, number, size, and arrangement of leaves (species attributes) are important factors that determine the photosynthetic area and capacity of individual plants. For example, multispecies plant communities such as homegardens that have multiple strata of leaf canopies and hence a much higher LAI, often translates to higher photosynthetic rates, compared to the sole (single species) stand of a crop. However, higher LAI need not necessarily lead to proportionately higher photosynthetic rates. One of the major considerations in the development of high-yielding varieties of cereals such as rice and wheat that led to the Green Revolution was the development of varieties that possessed a canopy with an optimum LAI with reduced mutual shading of leaves.

Application of the Beer-Lambert Law of Light Transmission: Solar-energy interception by different components of a multi-layered canopy with large vertical gaps between the constituent canopy units, and the distribution of PAR (photosynthetically active radiation) within these units, are important factors that determine the productivity of mixtures. In continuous-canopy crops such as cereals, light interception and distribution are governed by the Beer-Lambert law of light transmission:

$$I_i/I_o = e^{-kL}$$

Where,

I_i = PAR below the i^{th} layer of leaves
I_o = PAR above the canopy
e = natural log (2.71828)
k = a constant (called the *extinction coefficient*) depending, to some extent, on LAI and leaf characteristics
L = LAI

In practical terms, the equation means that the amount of PAR that is transmitted through a canopy is dependent upon the incident radiation and leaf/canopy features (angle, orientation, thickness, and arrangement of leaves and other light transmission characteristics) of the uppermost canopy layer. Various modifications of this basic equation have been suggested to describe light transmission patterns in discontinuous canopies such as agroforestry mixtures.

Existing information on optimizing such systems by proper choice of tree and crop species, however, is limited. In a five-year study in a planted silvopastoral system involving four tree species in peninsular India, Kumar et al. (2001) found that understory light availability (PAR is also known as PPFD, photosynthetic photon flux density) showed strong interspecific differences and the tree canopy characteristics determined the magnitude of canopy interception of incoming direct beam solar radiation. They also reported that understory herbage production followed a declining trend with the increasing interception of solar radiation by tree crowns; the understory production was particularly low under trees with dense spreading crowns. In addition to the selection of appropriate tree and crop components, tree-canopy manipulation through appropriate management treatments such as pruning, thinning, and others as described in Chapter 14 (Figure 14.3) is important for the success of the system.

Understanding how the components of a mixed plant community share solar radiation is a critical factor in the assessment and management of the productivity of agroforestry systems. The photosynthesis-light response curve saturates and levels off at about 25% full sunlight for most C3 plants (Figure 12.3). This response curve has two distinct phases: (1) a linearly rising limb at relatively low irradiance levels when the rate of photosynthesis increases proportionately as the irradiance level increases, and (2) a plateau region, with no incremental responses. Consequently, any leaf receiving more irradiance than the saturation level (i.e., beyond the point of inflection) may not be making full use of it. However, for most C4 plants this plateauing occurs much later, implying the potential of such plants for far greater photosynthetic efficiency than the C3 plants. Furthermore, there is acclimation to the lower light intensities within the canopy in terms of net photosynthesis, especially for C3 plants. For example, within the canopy of a particular plant, the exposed leaves (sun leaves) may have higher photosynthetic efficiency than leaves in the more shaded parts of the canopy (shade leaves); the latter are generally adapted to lower light intensities. Hence, even an "efficient C3" plant will have leaves in the more shaded parts of the canopy that are similar to the "C3 shade plant" curves in Figure 12.3. Yet another feature of C4 plants is the lower CO_2 compensation point (minimum CO_2 level at which the leaf can maintain a positive carbon balance; 0 – 5 μmol mol^{-1} CO_2 in C4, as compared to 40 – 50 μmol mol^{-1} in C3), which makes them more efficient in trapping CO_2 at lower concentrations. The C3 plant, however, is more efficient at higher CO_2 levels. The lower CO_2 compensation point of C4 plants implies PEP carboxylase activity (CO_2 concentrating mechanism) and reduction of photorespiration even at low CO_2 levels (Section 12.2). The multistory plant configurations presented in Chapters 7, 8, 11, and Figure 12.7 exemplify compatible plant associations consisting of the canopies of different species occupying distinct strata: the sparse-canopy (C3) trees at the top-most layer and the less-light-demanding (shade-adaptable) species at various distances below receiving adequate sunlight for them to function at their peak or near peak photosynthetic capacity. Agroforestry systems in the temperate zone, especially the temperate alley cropping consisting of growing C4 cereal crops in the alleys of hardwood timber species (Figure 10.1) are excellent examples of profitable exploitation of photosynthesis through plant arrangement and management. Equally impressive are commercial silvopastoral and intercropping systems involving fast-growing trees such as eucalyptus and poplar or cottonwood (*Populus* spp.) with C4 species such as maize and fodder grasses (C4 species) in the understory (Figure 12.8, also Chapter 9: Figures 9.12 and 9.13).

Another management option that is commonly discussed in the context of manipulation of photosynthesis for maximizing plant productivity for the "harvest of solar energy" is the row orientation (east-west vs. north-south). This is an important factor at locations farther north and south of the equator. It is common knowledge that summer days are longer at locations at, say, 40º N or S of the equator (such as the corn-belt of the USA) than at locations at or near the equator. When rows of plants point north and south, every row receives the same sunlight exposure during the day. Planting the crops in rows oriented east-west will result in a plant casting its shade on the plant next to it in the same row especially during early mornings and late afternoons. When rows of plants point north and south, every row receives

Figure 12.8 Commercial plantings of *Eucalyptus* hybrid in alleycropping with maize (*Zea mays*) in Minas Gerais, Brazil. (Photo: PKR Nair)

the same extent of sunlight-exposure during the day. An east-west orientation for the rows, however, can help the crops collect heat – an important factor when planted early in the season or when a cold snap occurs. These are not of much consequence in locations at or near the equator where there are hardly any seasonal differences in day lengths and heat (temperature) is not a limiting factor for crop production.

12.5 Conclusion

Understanding the principles of plant productivity and developing high-yielding varieties of cereal crops and their management practices based on those principles have led to the Green Revolution in the late 1900s, one of the most successful scientific achievements in agriculture. Those efforts were focused on uniform stands of single-species systems of cereal crops. Further efforts at extrapolating and applying these principles to combined production systems such as agroforestry consisting of multispecies mixtures of trees and crops of various forms and characteristics will be several-times more demanding and challenging, but, hopefully not impossible, and possibly rewarding.

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Multipurpose Trees (MPTs) and Other Agroforestry Species

13

Contents

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_13

Abstract

The multipurpose tree (MPT) is a term that is used almost exclusively in tropical agroforestry. In a general sense, the perennial and taller plant components of agroforestry systems (AFS) are referred to as trees, but the MPTs are woody species that are deliberately kept and managed for more than one preferred use, product, or service. Such species, relatively underutilized in commercial forestry and conventional agriculture are the distinctive components of most AFS in the tropics. Several of them are designated by single-purpose-sounding terms such as fodder trees, fruit trees, fuelwood species, and other special-purpose trees, but they provide multiple products and services. The MPTs have been a major thrust area of research in tropical agroforestry with emphasis on the collection, synthesis, storage, and dissemination of information at various levels (global, national, regional, etc.). The World Agroforestry *Agroforestree* database and the Agroforestry Species Switchboard launched in 2019 (http://www.worldagroforestry.org/products/switchboard/) document more than 26,000 plant species across 24 web-based information services that support agroforestry research. Several other global and regional databases are available and are listed in the chapter. The chapter also includes (Annexure 13-I) short profiles of about 60 commonly used MPTs in tropical AFS, with illustrative photographs of many. In addition, numerous other species that are important components of various AFS are designated as "lesser-known" or "less-prominent" taxa that include woody as well as non-woody, and seasonal or perennial species; Annexure 13-II includes profiles and photographs of ten such species. Brief notes are also included of a few unique high-value species traditionally grown in agroforestry combinations and are under the threat of extinction because of overexploitation for their high-value products.

13.1 Introduction

Trees are the most conspicuous and defining components of agroforestry systems. They include a variety of perennial plants that tower above other plants to compete for sunlight. The word (tree) is used in a broad sense to include all woody perennial plants including palms and bamboos; in some non-technical literature, non-woody plants such as banana (*Musa* spp.), papaya (*Carica papaya*), and tree ferns are also referred to as trees. The physical form or appearance (spread and height) of a tree species at a given location may vary depending on the ecological conditions; a species that grows luxuriously as a medium-sized tree in a wetter environment could be stunted and shorter, looking more like a shrub rather than a "tree," in a drier environment. Because of this lack of clarity, the word "woody perennial," rather than the tree, is used in some agroforestry literature. Nevertheless, the tree is still the most widely used term to refer to the perennial woody components of agroforestry systems (AFS).

13.2 Agroforestry Species

Many of the plant species – woody, as well as nonwoody – used in traditional AFS, are well known as conventional agricultural or forestry plants. During the development of agriculture and forestry as separate disciplines and operations, most of the species that were cultivated with higher managerial attention and were harvested at frequent intervals for their economic produce – either through repeated production of the same short-duration species or by repeated harvesting from the same plant – were classified as agricultural (for this discussion, horticulture is considered as a part of agriculture). Those species that were planted and usually managed less intensively, and harvested after a long production cycle, often for their wood products, were grouped under forestry (Nair 1980). There were also a few less important and relatively underexploited plants that did not fall clearly under either agricultural or forestry category. The emergence of agroforestry has brought a different perspective into these discussions on plant typologies based on their suitability for land-use systems. The most important characteristic that determines the place of a species in agroforestry is its amenability to integrated combination cultures (i.e., intercropping), irrespective of whether it is labeled as an agricultural, forestry, or any other type of species. Many of the relatively underexploited and lesser-known species – both woody and herbaceous – often satisfy this criterion much better than many of the well-known species. Several indigenous AFS involve a multitude of such species that are not widely known or used in conventional agriculture and forestry. Undoubtedly, one of the major opportunities in agroforestry lies in making use – "exploiting the potential" – of these lesser-known and underexploited species. The word exploitation is used here in a utilitarian rather than pejorative sense, emphasizing the opportunity to benefit from the diverse benefits provided by these species. Agroforestry places a special emphasis on making use of such lesser-known woody species, because they are (arguably) more numerous and less used (exploited) and therefore they offer greater scope for success in a variety of situations than herbaceous species, and because woody perennials are central to the concept of agroforestry as we have seen in Chapter 2. Thus, the term "agroforestry species" usually refers to woody species, and they have come to be known as "multipurpose trees" (MPTs) or "multipurpose trees and shrubs" (MPTS). This chapter is focused primarily on the MPTs in agroforestry; the less prominent species (both woody and herbaceous) and other plant components of AFS as well as the efforts and accomplishments in tree improvement in agroforestry will also be briefly included.

13.3 Multipurpose Trees (MPTs)

All trees are said to be multipurpose; some, however, are more multipurpose than others. In the agroforestry context, multipurpose trees are "those trees and shrubs which are deliberately kept and managed for more than one preferred use, product, or service; the retention or cultivation of these trees is usually economically but also sometimes ecologically motivated, in a multiple-output land-use system. Simply stated, the term 'multipurpose' as applied to trees for agroforestry refers to their use for more than one service or production function in an agroforestry system" (Burley and Wood 1991). This concept of MPT was further amplified by several others as they became fascinated by the scope and potential of such trees. For example, "Beyond rapid production of straight poles, MPTs help maintain or improve soil fertility, provide fodder, fruits, resins, medicinal bark or other products, as well as appropriate levels of shade and complementary rooting habits that ensure compatibility with crops" (Sinclair 1999).

As mentioned earlier, the MPT is the most distinctive component of agroforestry, and the success of agroforestry as a viable land-use option depends on exploiting the potential of these MPTs, many of them being relatively little-known outside their native habitat. It is incorrect, however, to assume that agroforestry species consist only of MPTs; indeed, the herbaceous species are equally important in agroforestry; so are the vines and other climbers. Many of these species are conventional agricultural species, and several textbooks describe them. The study of these species is an essential part of agricultural curricula. On the other hand, many of the MPTs used in agroforestry are neither described in conventional forestry or agricultural textbooks nor do they form part of such curricula. They include fodder trees, fruit trees, and fuelwood species, but the term MPT encompasses all such species in AFS. Such MPTs are given a special emphasis here.

13.3.1 Fodder Trees

Numerous tropical trees and shrubs that are traditionally known and used for their fodder in many developing countries became a major item of interest in agroforestry right from the early days. Le Houérou (1980)'s state-of-the-art account of the "trub" (a collective name for tree and shrub) species in Africa suggested that technologies based on permanent feed supply from fodder trubs could transform pastoral production systems into settled agropastoral systems. A review by Ibrahim (1981) presented a comprehensive treatment of the factors affecting dry-matter yield, palatability, nutritive value, and utilization of fodder trubs, including recommendations for further research and development. Torres (1983) presented another review of the subject including extensive information on trub species, their productivity, and nutritive value under different conditions, and concluded that protein supply was the main nutritive role of tropical trubs, but that the value could be limited by low levels of intake due to animal preferences. Further, several authors (Felker 1980; Le Houérou 1987) emphasized the importance of tropical trubs as a valuable source of animal fodder because of their presence and availability during dry seasons when grasses may be lacking or in states of extremely low nutritive value, and the pod-producing trubs are a useful source of energy and protein concentrate. Considerable interest had also been generated during the 1980s on the possibility of exploiting the fodder value of tropical leguminous trubs for improved silvopastoral management (Robinson 1985; Blair et al. 1990). Brief descriptions of most of these and other commonly used tropical tree and shrub fodder species are included in the MPT-summary (Table 13.1) and the species descriptions at the end of this chapter (Annexure 13-I). The nutritive values of the fodder of the common tree and shrub species used regularly in subsistence farming systems are variable depending on various factors such as the species, tissue type sampled, stage of growth, the season of sampling, and so on (see Table 13.2, pp. 174–175, in the first edition of this book: Nair 1993). The medium-to-high crude protein contents of the MPT fodders make them a valuable source of protein for livestock in the tropics. Individual descriptions on some of the important MPT fodder species are

Table 13.1 MPTs species selected for short profiles presented in Annexure 13.I

Acacia mangium
Acacia nilotica, A. senegal
Acacia senegal
Adansonia digitata
Ailanthus triphysa, A. excelsa
Albizia lebbeck, A. saman (*A. falcataria*= *Paraserianthes falcataria*)
Alnus acuminata, A. nepalensis
Artocarpus altilis, A. heterophyllus
Azadirachta indica
Bactris gasipaes
Borassus aethiopum, B. flabellifer
Bursea simaruba
Calliandra calothyrsus
Casuarina cunninghamiana, C. equisetifolia
Cedrela odorata
Ceiba petandra
Cordia alliodora
Dacroydes edulis
Dalbergia sissoo
Erythrina E. poeppigiana, E. berteroana
Euterpe oleracea
Faidherbia albida (*Acacia albida*)
Flemingia macrophylla
Gliricidia sepium
Grevillea robusta
Grewia optiva
Inga edulis, I. jinicuil, I. vera
Juglans regia
Juglans nigra
Khaya ivorensis, K. senegalensis
Leucaena leucocephala, *L. diversifolia*
Madhuca longifolia (*M. indica*)
Melia azedarach
Mimosa scabrella
Moringa oleifera
Paraserianthes falcataria (= *Albizia falcataria*)
Parkia biglobosa
Parkinsonia aculeata
Pongamia pinnata (= *Millettia pinnata*)
Poplulus deltoides
Propsopis chilensis, P. cineraria, P. juliflora, P. pallida
Robinia pseudoacacia
Samanea saman (see *Albizia saman*)
Senna (Cassia) siamea
Sesbania grandiflora
Sesbania sesban
Syzygium aromaticum, S. cuminii, malaccense
Tamarindus indica
Terminalia amazonica, T. browni, T. ivorensis, T. tomentosa
Vitellaria paradoxa (= Butyrospermum parkii)
Ziziphus mauritiana, Z. nummularia

Table 13.2 Selected attributes of some MPTs used in tropical and subtropical agroforestry systems

Species	Ecological Adaptation [1]	Growth form and characteristics [2]	Major uses or functions [3]
Acacia auriculiformis	E1/2, P3/4, alt, at, dt	30 m, poor coppicing	FW, Or, PW, SC, ST, (T), WLR
A. mangium	E1/2, P3/4, at, dt	30 m, coppices when young	FD, FW, PW, SB, SC, T
A. nilotica	E1, P2/3, dt	10 m, thorny, deciduous	A, DS, FW, G, SC, T, WLR
A. polyacantha (A. catechu)	E1/2, P2/3, low dt	25 m, good coppicing, spines	A, FW, G
A. saligna (A. cyanophylla)	E1, P1/2, alt, at, dt, st, wt	10 m, shrub, good coppicing	A, DS, FW, G, SB, SC, T, WLR
A. senegal	E1/2, P1/2, dt	10 m, thorny, deciduous	A, DS, FW, G, SC, WLR
A. seyal	E1/2, P1/2, dt	12 m, long thorns	A, FW, G, T, WLR
A. tortilis	E1/2, P1/2, alt, dt	15 m, thorny	A, FW, SC, T, WLR
A. xanthophloea	P1/2	20 m, spiny	A, FW, Or
Albizia chinensis	E1/2, P2/3	15 m, deciduous	A, ST, T
A. lebbek	E1/2, P2/4, at, alt, st	25 m, fair coppicing	A, CT, FW, Or, SC
A. odoratissima	E2	25 m	A, Or
A. (Samanea = Pithecellobium) saman	E1, P2/4, st	40 m, spreading crown	A, CT, F, Or, ST, T
Alnus acuminata	E2/3, P3/4, cool highlands	30 m, good coppicing	CT, FW, PW, SC, T
A. nepalensis	E2/3, P2/4, cool highlands	30 m, coppices	A, FW, GM, Or, PW, SC, T, WLR
Azadirachta indica	E1/2, P1/3, dt no N-fixation	15 m, coppices	A, FW, GM, M, O, PC, PW, SB, SC, ST, T, WLR
Balanites aegyptiaca	E1/2, P1/2, dt, no N-Fixation!	10 m, coppices	A, CT, F, FW, M, O, PC, T
Butyrospermum paradoxum	E1, P2, no N-fixation!	15 m, deciduous	F, M, O
Cajanus cajan	E1/3, P2/4, dt, st	5 m, shrub, many insect pests	A, F, GM, SC
Calliandra calothyrsus	E1/2, P3/4, at, (dt)	7 m, shrub, strong coppicing	A, BF, FW, GM, Or, SC
Cassia siamea	E1/2, P2/4, alt, at, dt, no N-fixation!	20 m, also as shrub, strong coppicing, strong root system	A, CT, FW, SB, SC
Casuarina spp. *(C. cunninghamiana, C. equisetifolia, C. glauca)*	E1/2, P2/4, alt, at, (ft), st, actinorhizal N-fixation	35 m, fast growth	CT, DS, FW, PW, SB, SC, T, WLR
Cedrela odorata	E1/2, P3/4, (ft), no N-fixation	up to 40 m	BF, CT, FW, T
Cordia alliodora	E1/2, P4), no N-fixation	30 m, deciduous, light canopy	CT, FW, Or, SF, ST, T
Dalbergia sissoo	E1/2, P2/4, at, (dt)	30 m, coppices, deciduous	A, CT, FW, Or, SC, ST, T
Diphysa robinioides	E1, P3/4	10 m, coppices	A, FW, GM, ST
Erythrina spp. *(E. berteroana, E. fusca = E. glauca, E. poeppigiana)*	E1/2/(3), P3/4, at	up to 25 m, thorny, coppices	A, GM, Or, ST
Faidherbia albida (Acacia albida)	E1/2, P1/2, dt, (ft)	20 m, thorny	A, CT, F, FW, GM, SF, T, WLR
Flemingia macrophylla (F. congesta)	E1/2, P3/4, dt	shrub to 3 m, coppices	A, GM, SC

(continued)

Table 13.2 (continued)

Species	Ecological Adaptation [1]	Growth form and characteristics [2]	Major uses or functions [3]
Gliricidia sepium	E1/2, P3/4, at, alt, dt, st	15 m, coppices, fast growth	A, BF, CT, FW, GM, Or, PC, SC, ST, T
Gmelina arborea	E1/2, P2/4, at, alt, (dt), no N-fixation	30 m, coppices, fast growth, deciduous	A, BF, CT, FW, PW, T
Grevillea robusta	E1/2/(3), P2/3, dt, no N-fixation	20 m, fast growth	BF, CT, FW, GM, Or, ST, T
Grewia optiva	E2, P3/4, alt	10 m, coppices	A, CT, F, Fi, FW
Hardwickia binata	E1, P1/2, dt, no report on N-Fixation	30 m, slow growth	A, DS, Fi, FW, SC
Inga spp. (*I. edulis, I. jinicuil, I. vera)*	E1/2, P2/4, at	20 m, coppices, wide crown	BF, CT, F, FW, ST, T
Leucaena diversifolia	E2/(3), P2/4, (alt), (at), dt	20 m, coppices, shrub or tree, fast growth	A, CT, FW, GM, PW, SC, T
L. leucocephala	E1, P2/4, (alt)	20 m, coppices, shrub or tree, fast growth	A, CT, F, FW, GM, PW, SC, ST, T
Melia azedarach	E1/2/(3), P2, dt), no N-fixation	30 m, coppices, fast growth	A, CT, FW, M, Or, PC, ST, T
Mimosa scabrella	E1/3, P3/4	12 m, coppices	FW, GM, Or, PW, ST
Moringa oleifera	E1/(2), P2/4), no N-fixation	15 m, coppices, open crown	A, BF, F, FW, M, O, Or
Paraserianthes (Albizia) falcataria	E2, P3/4, alt, at	40 m, coppices, fast growth	CT, FW, PW, SF, WLR
Parkia biglobosa	E1, P2/3, at, dt	20 m, coppices, deciduous	A, CT, FW, M, ST, T
Parkia javanica	E2, P3/4	40 m, coppices	CT, M, Or, T
Parkinsonia aculeata	E1/2, P1/3, dt, st, N-fixation?	20 m, coppices	A, F, FW, Or, SB, SC
Pithecellobium dulce	E1/2/(3), P2/3, dt	20 m, coppices, rapid growth; thorny	A, BF, CT, F, FW, Or, ST
Pongamia pinnata (syn. *Derris indica, Millettia pinnata*)	E1/2, P2/4, dt, st	8 m, shrub, spreads aggressively	A, CT, Fi, FW, M, PC, SC, ST
Prosopis alba, P. chilensis	E1/3, P1, dt, st	15 m, coppice, often shrubs	A, CT, F, FW, M, Or, T
P. cineraria, P. juliflora, P. pallida	E1/2, P1/2, alt, dt, st	10 m, coppice, often shrubs	A, CT, DS, FW, GM, SC, SF, T, WLR
Pterocarpus marsupium	E1/2, P2/3	30 m, coppices well	A, FW, M, T
Robinia pseudoacacia	E2/3, P2/3, dt	20 m, coppices, deciduous, rapid juvenile growth rate	A, BF, CT, FW, Or, SB, SC, T
Sesbania spp. (*S. bispinosa, S. grandiflora, S. sesban*)	E1/2, P2/3, alt, at, ft, st	5-10 m, coppice, often shrubs, fast growth, short lived	A, Fi, FW, GM, PW, Or, SC
Tamarindus indica	E1, P2/3, dt, (st) no N-fixation	30 m, coppices	A, BF, CT, F, FW, M, O, Or, ST
Terminalia catappa	E1, P3, st, no N-fixation	20 m, broad crown	A, CT, DS, F, FW, Or, SC, ST, T
Ziziphus spina-christi	E1/2, P1,2, dt	20 m, coppices, thorny	A, CT, FW, SC, T

Source: Adapted from Nair and Muschler (1993).

Notes:

[1]**Elevation zones**: E1 = lowlands (<500 m); E2 = mid elevations (500-1500 m); E3 = highlands (>1500 m).
Precipitation groups (total annual rainfall): P1 = < 500 mm; P2 = 500-1000 mm; P3 = 1000-1500 mm; P4 = > 1500 mm.
Tolerance to: alkaline soils = alt; acid soils = at; drought (> 3 months) = dt; flooding = ft; salt = st; wind = wt. Limited tolerance to certain attributes is indicated by brackets.
N_2 fixation: all spp. are documented N_2 fixers except when noted otherwise.

[2]All species are trees unless indicated otherwise.

[3]A=animal feed, BF=bee forage, CT=construction/craft timber, DS=dune stabilization, F=food (human consumption), Fi=fiber, FW=fuelwood, G=gum, GM=green manure, M= medicine; O= oil; Or=ornamental, PC= pest control; PW=pulpwood, SB=shelterbelts, SC=soil conservation, SF=soil fertility improvement, ST=shade tree (over plantation crops), T=timber and roundwood, WLR=wasteland reclamation.

also available in various special publications such as those by the U.S. National Academy of Sciences, Nitrogen Fixing Tree Association (NFTA), and others, on a range of species including *Leucaena* and *Calliandra*. Prominent among other publications of this nature during that period include those on *Gliricidia sepium* (Withington et al. 1987; Glover 1989; Stewart et al. 1996) and *Sesbanaia* (Evans and Rotar 1987; Macklin and Evans 1990).

13.3.2 Fuelwood Trees

It could be argued that any woody material can be fuelwood, and therefore any woody plant can be a fuelwood species. But the term "fuelwood (or, firewood) crops" as used in the literature refers to plants suitable for deliberate cultivation to provide fuelwood for cooking, heating, and sometimes lighting (Nair 1988). An international expert panel constituted in the late 1970s by the Board on Science and Technology for International Development of the U.S. National Academy of Sciences identified more than 1200 species as fuelwood species, of which about 700 were given a top-ranking, signifying that they were potentially more valuable than others. Eighty-seven of them were described in detail in a two-volume publication *Firewood Crops* (NAS 1980, 1983). In preparing these reports, special considerations were given to plants that have uses other than providing fuelwood; are easily established and require little care; adapt well to different ecological conditions, including problem environments such as nutrient-deficient or contaminated soils, sloping areas, arid zones, and tropical highlands; and have desirable characteristics such as nitrogen-fixation, rapid growth, vigorous coppicing, and wood of high-calorific value that burns without sparks or toxic smoke. Many of these commonly used or promoted fuelwood species are included in Table 13.1, and in the species (MPT) descriptions in Annexure 13-I).

13.3.3 Fruit Trees (see also Chapter 23, Section 23.3.1)

The indigenous farming systems of many developing countries often include numerous fruit- and nut-producing trees. These are common components in most homegardens and other mixed agroforestry systems; they are also integrated with arable crops either in intercropping mixtures or along boundaries of agricultural fields (Akinnifesi et al. 2008; Leakey 2012; Leakey 2020). These fruit trees are well adapted to local conditions and are extremely important to the diet, and sometimes even the economy of the people of the region, but they are seldom known outside their common places of cultivation. For example, an inventory of the commonly cultivated plants in mixed agroforestry systems in Tomé Açu, near Belém, Brazil listed 32 fruit-producing species, a majority of which were indigenous trees virtually unknown outside the region (Yamada and Osaqui 2006). Examining the biological and socioeconomic attributes of fruit trees and their role in agroforestry systems, Nair (1984) concluded that fruit trees are one of the most promising groups of agroforestry species. Given the importance of agroforestry in food and nutritional security, the topic is discussed in more detail in a separate chapter (Chapter 23). A summary account of the occurrence of the common fruit trees in tropical agroforestry systems, their condensed crop profiles, and proximate food composition of their products are included in that chapter (see Tables 23.1, 23.2, and 23.3). There are many more fruit tree species that are either already present in existing agroforestry systems or could potentially be used in agroforestry combinations. Detailed descriptions of several of the better-known fruit trees are available (e.g., Morton 1987), mostly from the 1990s or before; once again, readers are advised to refer to these specialized publications for details.

13.3.4 Other Underexploited Woody Perennials

The history of agroforestry development, albeit short, is dominated by the emphasis and focus on a few (50 +) species of trees and shrubs (shown in Table 13.1 and the species descriptions in Annexure 13-I). Some of these have received considerably more attention than others. Given that worldwide agricultural efforts are concentrated on about 25 plant species, the emphasis of agroforestry on twice that number of MPTs may appear to be good. Nonetheless, in many developing countries, rural populations derive a significant part of their food and other basic requirements from various indigenous trees and shrubs that are seldom "cultivated." In addition to food, these species provide a variety of products such as fiber, medicinal products, oils, and gums, which play a critical role in meeting the basic needs of local populations. Numerous such indigenous MPTs have been identified and their multiple roles in providing food and nutritional security, medicines, cash income, and a whole host of other products and benefits have been recognized (e.g., Elevitch 2006). Many of these species occur naturally in forest environments that are currently under pressure as the demand for agricultural land increases. Furthermore, these species are often complementary to agricultural crops and animal products. They may serve as emergency supplies in times of drought and they are usually consumed at production points with only a fraction of the products entering the local markets. Therefore, the variety and value of products that are derived from such trees are seldom appreciated, and, consequently, no efforts have been made for their domestication, improvement, or exploitation. Clearly, a major prospect, as well as the challenge of agroforestry, lies in domesticating, improving, and exploiting the multitude of these indigenous MPTs.

Various publications during the 1980s and 1990s from FAO and other sources list information about the various indigenous food- and fruit-bearing trees and shrubs in different parts of the tropics (e.g., FAO/SIDA 1982; FAO 1983a, 1983b, 1984, 1986a, 1986b). As discussed in Chapter 7, tropical homegardens and multistory tree gardens contain numerous such locally adapted woody perennials. For example, Fernandes and Nair's (1986) analysis of homegarden systems in 10 selected countries identified about 250 woody perennials of common occurrence in these homegardens. Similarly, Michon et al. (1986) and Okafor and Fernandes (1987) reported the presence of many such species in Indonesia and Nigeria respectively. Some of these are relatively better-known fruit trees described in Chapter 23 (Table 23.2). A vast majority of these species, however, are quite restricted in their distribution and are virtually unknown outside their usual range. Numerous emergency food plants that are less preferred during normal times are consumed when regular food crops are not available. FAO (1983a, 1983b, 1984) has identified 700 such species that are used as emergency food sources; a vast majority of them are woody perennials and components of existing indigenous agroforestry systems.

The U.S. National Academy of Sciences publication (NAS 1975) and Vietmeyer (1986) list several other underexploited species of promising value, and some of these are multipurpose woody perennials that can be incorporated into agroforestry systems. ICRAF's computerized MPT database contains more than 600 species entries based on literature searches and actual field reports (van Noordwijk 2019). Even species like the Brazil nut tree (*Bertholletia excelsa*), guarana (*Paullinia cupana*), passion fruit (*Passiflora edulis*), cupuaçu (*Theobroma grandiflorum*), and durian (*Durio zibethinus*), which are very common in specific parts of the tropics, are not fully exploited despite their tremendous potential. In the dry regions too, there are several such multipurpose woody species, the most notable being the various *Prosopis* spp., that can be incorporated into agroforestry (especially silvopastoral) systems. Palms are another group of multipurpose woody species with tremendous potential in agroforestry as discussed in Chapter 8 (Section 8.6, Table 8.5). Undoubtedly, making the best use of the vast range of underexploited species is one of the most promising opportunities in agroforestry.

13.3.5 MPT Databases

The collection and synthesis of information on MPTs was a major effort by ICRAF and others during the early stages of agroforestry development during the 1980s and early 1990s. Various national agroforestry initiatives (Chapter 1) developed their own information bases and species inventories for use in their specific activities. Since computerized databases were not fully functional during those days, most of such information was stored in "hard" (paper) files and publications. These included general databases involving different types of MPTs and specialized ones for species yielding specific products and services such as fodder, fuelwood, nitrogen-fixation, etc., and as publications on individual species. While computerization has greatly improved the storage, categorization, and retrieval of information about MPTS, the basic understanding of the characteristics of the species is practically the same in both conventional and modern databases.

Early ("Hard") Databases. Notable general information sources included:

- The U.S. National Academy of Sciences (NAS) publications on Firewood Crops (NAS 1980, 1983) and individual publications on some taxa such as *Leucaena*, *Acacia*, *Casuarina*, and *Calliandra calothyrsus*
- A compilation of information on the most important MPTs in dryland Africa (von Maydell 1986)
- The ICRAF Multipurpose Tree and Shrub Database (von Carlowitz et al. 1991), a comprehensive compendium on the subject based on extensive field surveys
- A compendium on MPTs used in Asia, prepared by Winrock International (Lantican and Taylor 1991)
- Multipurpose Australian Trees and Shrubs: lesser-known species for fuelwood and agroforestry (Turnbull 1986).

Computerized MPT Databases. With the widespread availability of computerized facilities for collection, synthesis, storage, and dissemination of information since the mid-1990s, there have been several efforts at various levels (global, national, regional, etc.) in building up such MPT databases and other publications including scientific literature. The most significant among the MPT databases at a global level is ICRAF's *Agroforestree* database (ICRAF 2006; Orwa et al. 2009). A revised "Agroforestry Species Switchboard" was launched in 2019 (http://www.worldagroforestry.org/products/switchboard/), which is described as a "one-stop-shop" to retrieve data about any specific plant species across a wide range of information sources. It documents more than 26,000 plant species across 24 web-based information services for providing information that supports research on tree-based development activities such as agroforestry (Kindt et al. 2016, 2019). The *GlobalTreeSearch* by Botanic Gardens Conservation International (http://www.bgci.org/global_tree_search.php; https://www.bgci.org/resources/bgci-databases/globaltreesearch) is the most comprehensive database of tree species with information on over 60,000 tree species and their global distributions; only 1% of these are currently included in the *agroforestree* database (ICRAF 2006; van Noordwijk 2019). The *Plant List* (www.theplantlist.org), launched in 2013 (as a collaborative effort of Royal Botanic Gardens, Kew, UK, and the Missouri Botanical Garden, USA, is a working list of all known plant species. Numerous other plant databases of relevance to agroforestry are available; for example, the *USDA Food Composition Databases,* the *Wood Database, the Tropitree Database,* and so on. Other specialized databases include shade trees for shaded perennial AFS described in Chapter 8, the CABI (2019) Invasive Species Compendium, and the database on food and fruit-producing trees in agroforestry discussed in Chapter 23. A list of various tree databases at global and regional levels is also presented in Chapter 23 (Table 23.4).

13.3.6 MPT Species Profiles

A compilation of the important characteristics and uses of about 50 MPTs (listed in Table 13.1) that are commonly used in agroforestry systems around the world is presented in Table 13.3, and brief descriptions (Species Profiles) of individual species along with photographs of some of them are provided at the end of this chapter (Annexure 13-I). The species list is not at all exhaustive; it merely represents some MPTs that have received research attention and are therefore more widely known than others, as well as some lesser-known

Table 13.3 List of some African tree species being domesticated for their Agroforestry tree products

Species name	Common name	Product	Use
Adansonia digitata	Baobab	Leaf, Fruit	Food
Allanbachia spp.	Nsangomo	Kernel	Oil
Chrysophyllum albidum	White star apple	Fruit	Food
Dacryodes edulis	Safou	Fruit	Food and oil
Irvingia gabonensis	Bush mango	Kernel	Food thickening
Garcinia cola	Bitter cola	Kernel	Stimulant
Gnetum africana	Eru	Leaf	Food
Parkia biglobosa	Néré	Kernel	Food
Prunus africana	Pygeum	Bark	Medicine
Ricinodendron heudelotii	Njangsang	Kernel	Spice
Tamarindus indica	Tamarind	Fruit	Food
Vitellaria paradoxa	Shea nut	Kernel	Food
Zizyphus mauritiana	Ber	Fruit	Food

Source: Adapted from Leakey (2017)

species that seem particularly promising. Out of an estimated global total of over three trillion (3.04 x 10^{12}) trees in the world (Crowther et al. 2015), 60,065 tree species that constitute 25% of all angiosperm and gymnosperm plant species are currently known (Beech et al. 2017), and a significant number of them can be assumed as existing in some form of agroforestry-type plant associations providing multiple products and services. Any shortlist of 50 or 100 species out of this vast number cannot be truly representative of the entire population. Yet, various research reports have focused on such relatively small numbers (50 to 100) of MPTs. For example, van Noordwijk (2019) listed "top-40" MPTs listed in at least 19 databases; Wolz and DeLucia (2019) found that 410 tree species from 192 genera were reported in agroforestry literature from 77 countries; de Sousa et al. (2019) identified 100 trees used as shade trees in coffee and cacao agroforestry systems in Mesoamerica, and so on.

It was in this backdrop that the species list and tree profiles included here were prepared. Popular and well-known timber species such as teak (*Tectona grandis*) and mahogany (*Swietenia* spp.), and other plantation forestry species such as pines (*Pinus* spp.) and eucalypts (*Eucalyptus* spp.) are not included here because the literature on such species is abundantly available. However, these species are included in agroforestry associations such as the *taungya* (Chapter 5) and silvopastoral systems (Chapter 9); indeed, most of the silvopastoral systems, especially in commercial enterprises and industrialized countries include such commercial forestry species. Another group of MPTs though common in AFS but not included in the species list here are the fruit trees in both the tropical regions [e.g., mango (*Mangifera indica*), avocado (*Persea americana*), guava (*Psidium guajava*), and so on] and the temperate regions [e.g., apple (*Malus domestica*), pear (*Pyrus* sp.), peaches (*Prunus persica*), and so on]; on the other hand, relatively lesser-known fruit trees such as *Artocarpus* spp. are included in the species profiles, because they are less well-known compared to the major species, but yet are components of AFS in their preferred habitats (lowland humid tropics). Another feature of the species profiles is that multiple species of the same genus with comparable phenotypical characteristics are presented mostly under one profile when they all have similar growth habits and ecological distributions. However, species of some genera do not have such similarities in ecological adaptation or phenotypical appearance; in such cases, species profiles are included for multiple species of the same genus; for example, *Acacia mangium, A. nilotica,* and *A. senegal* are presented separately, but several other species of *Acacia* that are known as components of AFS are not included for reasons of brevity).

13.4 Lesser-Known Agroforestry Species

In agroforestry literature, the term “agroforestry species” usually refers to woody species that have come to be known as multipurpose trees (MPTs) for reasons and circumstances explained at the beginning of this chapter (Section 13.2). In addition to the MPTs, however, numerous other species are important components of various AFS. Indeed, the very concept of agroforestry is rooted, simply stated, in growing trees and crops (or, to be technically more correct, woody and herbaceous species) together on the same unit of land. Therefore, any AFS should have at least one other component than the woody perennial (except in special circumstances such as block planting of trees for land reclamation purposes). The terms “lesser-known” or “less-prominent” species are used here to refer to species of any kind (woody or non-woody, seasonal or perennial) other than the “designated” MPTs in AFS. It may be a misnomer to refer to them with “less” as a qualifier because they are equally – sometimes even more – important as the MPTs. Indeed, most of them are MPTs in terms of the multiple products and services they offer, especially the various overstory species mentioned in Chapters 7 (Homegardens), 8 (Shaded perennial systems), and others. Several categories of such species are used in AFS including annuals and perennials of various lifespans, growth habits (herbaceous, woody, or trailing vines), and harvest cycles (seasonal or throughout the year). The following section will briefly describe just a few examples of the common species used around the world under the broad categories of shade-tolerant specialty, perennial species. Also listed are some unique high-value species traditionally grown in agroforestry combinations that are under the threat of extinction because of overexploitation for their high-value products of commerce.

13.4.1 Shade-Tolerant Specialty Crops and Medicinal & Aromatic Plants

In addition to the shaded perennial crop combinations involving major commercial plantation crops such as cacao, coffee, coconut, and oil palm that are described in Chapter 8, several such integrated production systems involving specialty crops exist, especially in the tropics and subtropics. These species require relatively more exacting growth requirements (climate, soil, and other ecological conditions) and management attention and skills for cultivating them and processing their products, and the final yields of the processed products are relatively small in quantity per unit area of land. The extent of area under such species is comparatively smaller than that of the “major” shaded perennial systems; however, the products are high-value commodities of international trade such that the additional attention needed for their production and processing are financially well worth it.

Such specialty crops that are mostly perennial in growth habits and are non-destructively harvested every fruiting season like fruit trees fall under the following broad categories:

1. **Commercial crops trailed onto woody perennial support trees** (perennial vines); Prominent examples: black pepper (*Piper nigrum*) and vanilla (*Vanilla planifolia*),
2. **Perennial rhizomatous cash crops** that are grown under the shade of trees in natural stands and harvested like annuals; Prominent examples: cardamom (*Elettaria cardamomum*) and large cardamom, (*Amomum subulatum; A. aromaticum*),
3. **Rhizomatous, botanically perennial species that are cultivated as annuals** under planted or natural stands of trees; Prominent examples:

ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), ginseng (*Panax* spp.), and

4. **Medicinal and aromatic plants**, mostly annuals but also including some trees that are harvested annually and nondestructively like fruit trees; Prominent examples: allspice (*Pimenta dioica*, clove (*Syzygium aromaticum*), nutmeg (*Myristica fragrans*).

A considerable amount of information exists on the management and processing of almost all the crops mentioned above, particularly for those cultivated for their high-value commercial products such as black pepper, cardamom, clove, ginger, etc. Substantial research-based advancements have been made in the varietal improvement, agronomy, pest and disease management, postharvest processing, and production economics of these plants, given their economic importance. However, true to the legacy of sole crop agronomy that is followed in most such agroforestry situations, most available management recommendations are compiled as though the species are cultivated as sole crops with little or no details on agroforestry-specific information such as shade requirement of the species concerned and management of shade trees. Brief notes and some photographs of some of the examples of the four categories of specialty perennial crops mentioned above are presented as Appendix II to this chapter. Descriptions of some agroforestry systems involving medicinal and aromatic plants are included in Chapter 11, Section 11.3.3.

Several tubers, e.g., cassava (*Manihot esculenta*) and sweet potato (*Ipomoea batatas*), yams (*Dioscorea* spp.), taro (*Colocasia* spp., *Xanthosoma* spp.) that are either sciophytes (requiring variable degrees of shade for their optimal performance), or perennial vines that tolerate a certain degree of shading, are also used in AFS. Their products are bulky and edible and rich in carbohydrates but low to poor in nutritive value, and are edible and labeled as poor mans' food; nevertheless, given their wide adaptability, low economic and nutritional values, ease of care and management, and non-requirement of elaborate post-harvest processing, they are not considered as specialty crops in this discussion. On the other hand, several species of perennial vegetables and trees with edible leaves are popular components of homegardens and other agroforestry combinations in different ecological regions. Examples include the table olives (*Olea europaea*), avocado, the moringa tree (*Moringa oleifera:* see the species profiles in Appendix I of this chapter, and Figure 13.A.I.16), and numerous others. These species constitute a group of vegetables with relatively high levels of multiple nutrients and thus are "multi-nutrient" species with enormous potential for exploitation under agroforestry systems (Toensmeier et al. 2020).

13.4.2 Agronomic and Horticultural Species in Agroforestry Systems

In the history of agricultural domestication and improvement of plants, attention has focused on nearly 30 species that have come to comprise most of the world's human diet (Borlaug and Dowswell 1988). Understandably, the selection and improvement programs of these species have mostly been oriented toward those traits and characters that would render the improved cultivars most suitable to maximal production under sole-crop conditions. Agroforestry settings, however, offer sub-optimal conditions for the growth of most of these plants as regards the availability of resources such as light, moisture, and nutrients. Thus, we are in a difficult situation concerning the so-called agricultural species for agroforestry. On the one hand, an important measure of success of agroforestry is its ability to satisfy the farmers' expectations and aspirations regarding the production of their most basic need (i.e., food); this implies that some of these nearly 30 preferred crop species should be produced in a given agroforestry system. On the other hand, crop improvement efforts have not addressed the need to select or breed varieties of these species which can thrive in low-input and mixed culture conditions. The situation has been made even more difficult with all the emphasis on agroforestry species being placed on MPTs almost at the exclusion of agricultural species.

The agroforestry potential of the traditional agricultural species is different from their commonly perceived production potential. Based on the knowledge of the ecophysiological requirements of different groups of plants in general, and the individual species or cultivar in particular, some predictions can be made with reasonable accuracy about optimal conditions for their best growth. It is also possible to predict the ability of the species to produce a reasonable yield under conditions of reduced supply of basic growth factors such as light, nutrients, and water. Furthermore, from the practical point of view, the ease of management of the species, its ability to withstand adverse climatic and management conditions, and its adaptability to low-input systems are important considerations. Predictions regarding compatibility and agroforestry potential of common crops could be made based on the information about their performance under diverse agroforestry systems, as well as available knowledge about their growth requirements. Numerous textbooks and other resources that describe the botany and agronomy of cultivated plants are available. For example, Purseglove's books (Purseglove 1968, 1972) are the classics in this regard, and they give a comprehensive treatment of the subject. Several other modern books and publications are available as well. Some preliminary efforts in identifying the agronomic species for agroforestry were initiated by Nair (1980) in his compilation, *Agroforestry Species: A Crop Sheets Manual*, published by ICRAF (now out of print). Unfortunately, this type of work has not been seriously pursued in agroforestry. While rectifying this deficiency, attention should also be given to other relatively underexploited herbaceous species of potential value in agroforestry.

Another group of plants, equally important in agroforestry as the agronomic crops, are the horticultural crops. Just as in the case of arable crops, numerous plants that are known broadly as horticultural crops (vegetables, fruits, and even ornamental plants) are important components of agroforestry systems. And, from the perspective of agroforestry, the horticultural species are comparable to the agronomic species not only in terms of their diversity and adaptability to different AFS and the abundant literature that is available on their details but the lack of any serious efforts to select and promote any such species that are particularly suitable for agroforestry situations.

13.4.3 Overexploited (Endangered) Species

Several high-value woody perennial species that are often grown in agroforestry systems in the tropics and subtropics are subjected to severe overharvesting to the extent that they are endangered and threatened with extinction. Although some of them are protected by the local authorities, the illicit operations usually take the upper hand in such situations. Two "classical" examples are the sandalwood tree of India and East Asia and the African cherry tree. American chestnut (*Castanea dentata*), native to eastern North America, is an example of an endangered tree species that has been almost completely devastated by the dreaded chestnut blight disease.

The Sandalwood Tree (***Santalum album***, Santalaceae): Also called the East Indian sandalwood tree, it is an evergreen, slow-growing species native to India and Indonesia. It grows 10 to 13 m tall, attaining a trunk girth of 100 to 160 cm in about 30 years after planting (Figure 13.1). Among the ten species of the genus *Santalum*, the most popular and valuable is *S. album*. The wood is heavy, yellow to off-white, and fine-grained; unlike many other kinds of aromatic wood, they retain their fragrance for decades. Sandalwood is hemiparasitic and can

Figure 13.1 A sandalwood tree plantation in Sabah, Malaysia. The species is facing extinction due to overexploitation because of the high international demand for its wood. (Photo: PKR Nair 2007)

thrive only if it grows alongside (within a meter distance from) another already established "host" plant to which the roots of sandalwood get attached and derive the nutrient supply until the sandalwood can be self-supportive, usually within a year. Wattle trees (*Acacia* spp.), *Casuarina* spp., and pigeon pea (*Cajanus cajan*) are good examples of host species, and the host plants are often retained even after the sandalwood is "self-supporting." It takes 30 or more years for the tree to attain merchantable-size wood. Even before it reaches that stage, it is subjected to illegal harvesting. Outright stealing of the species traditionally grown in natural forests/government-owned forest plantations is so rampant in the sandalwood-growing regions of southern India that the species is heavily protected (see Figure 13.2). In India, sandalwood cultivation on private lands used to be restricted by the state governments; the regulations have lately been relaxed in several states; consequently, farmers have taken up sandalwood cultivation, intercropped with other species on private farms. Its leaves are used as animal feed as well. Sandalwood is the second-most expensive wood in the world, after the African blackwood (*Dalbergia melanoxylon*). Both the wood and the oil extracted from it produce a distinctive fragrance that has been highly valued for centuries. Australian

Figure 13.2 Barbed wire fencing is erected around a sandalwood tree to protect it from being stolen, on the campus of the Institute of Wood Science and Technology, a forestry research institute of the Central (Federal) Government of India in Bengaluru (Bangalore), India. (Photo: PKR Nair 2017)

sandalwood (*Santalum spicatum*) is a tree native to the semiarid areas of Southwest Australia, the oil of which is also used as a valuable aromatic.

African Cherry (*Prunus africana*, Rosaceae)**:** It is an evergreen tree, 10 – 30 m tall, with a stem diameter of up to 1 m, blackish-brown and rugged bark, and a lifespan of about 80 years. The bark is used by pharmaceutical companies to manufacture a drug (*Tadenan*) used in treating prostrate problems of elderly men. Once well-distributed throughout Africa, from Ethiopia to South Africa and from the west coast to the island of Madagascar, the tree has been ruthlessly exploited since its medicinal properties became widely known. Traditionally, debarking begins when the tree is about 15 years old and 30 cm girth diameter, at about a meter from the ground to the first branch. Half of the bark is split upright using a machete (*panga*), leaving the other half to be harvested four years later after the initially debarked area covers up, thus allowing a well-looked-after tree to be debarked six or seven times during its lifespan. The tree is grown in association with other trees and crops in homegardens. Consequent to its disastrous overexploitation, *Prunus africana* is now protected by the international treaty, CITES (the Convention on International Trade in Endangered Species, https://cites.org), and its export is subject to CITES approval; unfortunately, however, illicit traders circumvent such restrictions.

American Chestnut (*Castanea dentata,* Fagaceae): A large monoecious deciduous tree native to eastern North America and once considered the finest chestnut in the world has been almost completely devastated by chestnut blight, a fungal disease, in the early 1900s; now it is listed as an endangered species. Hundreds of large (0.5 to 1.5 m diameter) trees still exist outside its historical range. Currently, there are programs to revive the American chestnut tree by cross-breeding it with the blight-resistant Chinese chestnut (*Castanea mollissima*). Unlike in the tropics and subtropics where prominent MPTs are designated as agroforestry trees, there are no tree species in North America and other temperate regions that are known distinctly as agroforestry species. Even so, the chestnut tree as a major multipurpose species with its edible nuts and valuable timber is often mentioned in the agroforestry literature.

13.5 Tree Improvement in Agroforestry

Improved germplasm developed through selection and breeding has been the main foundation for the phenomenal increases in the quantity and quality of products that were attained for several food crops during the second half of the twentieth century. Similar improvements have also been accomplished for some fruit trees, commercial tree crops (e.g., rubber), and a few timber species such as pines and eucalyptus. But the track record of four decades of tree improvement in agroforestry has fallen short of the expectations and promise of agroforestry.

13.5.1 A Brief Account of Accomplishments

Tracing the history of tree domestication in forestry vs. agroforestry, Simons and Leakey (2004) pointed out three major differences between the two sectors: the number of taxa involved, the commercial (industrial) rather than the subsistence use, and the number of stakeholders involved. Commercial forestry plantations are specialized operations that typically handle one or a few species, where one company or enterprise will handle all operations from germplasm sourcing, planting, nursery and field management, harvesting, and post-harvest processing, all carried out with the focus on profit maximization. Agroforestry, on the other hand, is a much more complex set of activities, involving hundreds of tree species and millions of small-scale farmers interested in a multitude of products and services, and numerous private, public, international, and non-governmental organizations; moreover, most operations are concerned with on-farm use of the products and services. Thus, while "genetic tree-improvement" can only deal with a few tree species at the required level of research intensity, farmers and rural communities may require tree diversity to ensure their livelihoods and landscapes (Jamnadass et al. 2019; van Noordwijk 2019).

The major efforts in MPT improvement under the leadership of ICRAF until the early 1990s included the creation of an MPT database (von Carlowitz et al. 1991) and field trials of MPT screening and evaluation at various places (Nair and Muschler 1993). The overall strategy focused on tree domestication involving collection, screening, and evaluation of the available germplasm. The genera that received the most attention included *Dalbergia, Erythrina*, *Gliricidia*, *Leucaena*, and *Sesbania*.

Recognizing the special conditions and challenges to be faced in agroforestry referred to above, ICRAF reoriented its tree domestication program in agroforestry in a different direction since the mid-1990s (Simons and Leakey 2004; Leakey et al. 2012). The principal activities envisaged under this initiative were the assessment of species potential and the development and dissemination of the techniques for improved germplasm production. The scope of the activities was later broadened to include characterization of genetic variation using morphological and molecular techniques, product commercialization, adoption and impact assessment, and protection of farmers' rights. Increasing the use of laboratory techniques to quantify the genetic variation of the chemical and physical composition of marketable products such as essential oils, food-thickening agents, pharmaceutical and nutraceutical compounds, and fuelwood was also envisaged. Numerous reports and publications are available outlining such ambitious action plans covering a wide variety of tree species in the various developing regions of the world that are frequently mentioned in agroforestry literature (Leakey et al. 2012); however, quantitative information on the extent to which the program has been implemented and the nature of benefits realized is still awaited.

The approaches to tree domestication in agroforestry and the methods used vary depending on several factors including tree biology, conditions of the planting site, expected uses and value of the anticipated products and services, level of infrastructural facilities, and so on. Two basic approaches have been proposed (Leakey et al. 2008; Jamnadass et al. 2019). The first is the traditional centralized approach involving extensive field trials that is applicable to both commercial plantations and smallholder farms. The second, following the overall ICRAF strategy outlined above, is a decentralized community-driven, "low-input breeding approach" that is now (2020) being pursued (Jamnadass et al. 2019). Based on the concept of "community participation in tree domestication" (Tchoundjeu et al. 2010) and developed in collaboration between scientists and the farming community, it involves scientific advances in tree improvement with local communities' experience in tree management, particularly in bringing indigenous fruits and nuts into wider cultivation. Table 13.3 gives a list of some African tree species being domesticated for their agroforestry tree products through the process described by Leakey (2017) as "Socially modified organisms in multifunctional agriculture." In conjunction with a related initiative, "African Orphan Crops Consortium" (http://africanorphancrops.org), this approach is expected to overcome some of the challenges involved in linking genetic improvement and germplasm multiplication to smallholder farmers' needs (Jamnadass et al. 2019).

Another noteworthy effort in tree improvement in agroforestry is the remarkable work that has been going on for the past few decades and the significant accomplishments in germplasm improvement of *Bactris gasipaes* (peach palm, *Pupunha*: see Annexure 13.I for the species profile) under the leadership of C. Clements in INPA (National Institute of Amazon Research), Manaus, Brazil (https://www.inpa.gov.br).

13.5.2 Ideotypes of Agroforestry Trees?

Plant breeding techniques that have been successfully employed have helped revolutionize plant production in agriculture, forestry, horticulture,

Table 13.4 Example of an Ideotype specifications for *Acacia tortilis* for use in agroforestry systems in semiarid regions

Design Needs	
• Products and services required	• Fodder, fuelwood, food, windbreak, poles, shade
• General selection criterion	• Vigor
• Ancillary information required	• Nitrogen-fixing (or not), Chemical composition (fodder value) of leaves and pods
Ideotype Description	
• Stem	• As straight as available, multiple stems acceptable
• Crown	• Fairly rounded (crown: bole ratio: 25:1 or less)
• Roots	• Angled rather than horizontally extending lateral roots
• Pods	• Large pods (av. 60 – 100 cm long, > 8mm wide)
• Thorns	• As small and as few as can be found
• Response to management	• Prolific regrowth after pruning, pollarding, coppicing
• Deciduousness	• Low period of leaflessness

Source: Adapted from Wood (1990); Burley and Wood (1991) with permission from John Wiley for Nair (1993)

and other land-use activities, but not in agroforestry. The pioneering work on the genus *Leucaena* in the 1980s and 1990s (Brewbaker 1987) is, perhaps, the only effort in this area; but that pales in comparison to such efforts made for, rice, maize, other crop plants or eucalyptus. The concept of ideotype that plant breeders use in designing the strategy for breeding new germplasm may perhaps be worth considering when rather than if breeding desirable plant types gets started seriously (Table 13.4).

An ideotype, "a form denoting an idea," refers to a biological model that is expected to perform predictably within a defined environment. Originally developed for agricultural crops using the conventional "selection for yield" approach (Donald 1968) to specify the ideal attributes of a plant for a particular purpose, the concept has been adopted in many crop breeding programs (Adams 1982). It has, however, not become a major operational part of most tree breeding programs (Dickmann 1985; Dickmann et al. 1994). As mentioned in the previous section, the early efforts in MPT improvement during the 1980s focused on identifying the species, varieties, provenances, and cultivars of MPTs that are most promising and deemed appropriate for a given set of conditions and objectives. One of the difficulties encountered in those efforts arose from the very reason for choosing an MPT, i.e., its multiple uses and roles, such that the focus on one product or service may affect or even contradict the output of other products and services. For example, leaf production will be an important attribute of an MPT developed or selected for its green-manure value; the same species, if improved or developed for fuelwood production should produce a higher proportion of its biomass as shoots. Therefore, for each species, the screening and selection criteria will have to be specific depending on the objectives and locations. Thus, nothing approximates an "ideal" MPT for all locations and purposes. *Faidherbia* (syn. *Acacia*) *albida* (Figures 9.8, 9.9, 9.10), acclaimed as *the* agroforestry tree for intercropping, because of its remarkable phenology of losing its leaves during the rainy season when the arable crops are grown under the trees, and the leaves sprouting back at the beginning of the ensuing long, dry season in its native drylands of West Africa, is not the "ideal" species for other forms of agroforestry and other regions.

As Wood (1990) pointed out, structural, physiological, phenological, and management characteristics should be included in the description of an ideotype for a specified situation in agroforestry. An example of the desired ideotype of *Acacia tortilis* for agroforestry in the semiarid environments (Table 13.3), suggested by Wood (1990) and Burley and Wood (1991), illustrates the complexities involved in conceptualizing ideotypes of MPTs for agroforestry. Furthermore, the interest in any specific MPT may lie in several of its attributes, and these may behave in quite different or even opposing ways for changes in desired products of the species, or even sites. Recommendations on tree ideotypes for agroforestry may, therefore, have to adopt a "cafeteria" (instead of a “set menu”) approach, by which it will be possible to define the specific features of an MPT for a given set of conditions.

Leakey and Page (2006) reported that “fruit” and “kernel” ideotypes have been identified in *Irvingia gabonensis* (bush mango) in the west and central Africa, based on quantitative characterization of a number of fruit, nut, and kernel traits. The “kernel ideotype” has been subdivided into “oil” and “food-thickening”' ideotypes, with options for further subdivision of the latter into ideotypes with either high or low viscosity characteristics. Similar opportunities for the development of single-purpose cultivars from multipurpose species have been identified in the *Marula* tree *(Sclerocarya birrea*). Leakey and Page (2006) further reported that in *S. birrea* and *Dacryodes edulis*, future options exist to extend ideotypes with recognition of the variability in both nutritional and organoleptic qualities. Clearly, tree ideotypes could be a useful tool for visualizing and conceptualizing how to combine specific rare combinations of visible and invisible traits, aimed at the maximization of desired benefits, even when the traits are only weakly related.

13.6 Concluding Remarks

Multipurpose trees and other agroforestry species are the most distinguishing components of agroforestry systems. Nature, arrangement, and management of these components as overstory and interplanted understory species determine the performance of the systems. During the past more than four decades of agroforestry development, considerable efforts have been made to bring these species, especially the multipurpose trees, which had been underexploited and relatively unknown or forgotten until then, to the forefront of research and development efforts. The efforts and enthusiasm in this direction seem to have slowed down gradually. The selection and improvement of agronomic species for agroforestry conditions have not even been attempted to any notable extent. The promise of agroforestry cannot be realized, nor the expectations fulfilled unless this trend is reversed.

Appendices

Appendix I: Short Descriptions of Multipurpose Trees and Shrubs (MPTs) Commonly Used in Agroforestry Systems

These descriptions include essential information on the taxonomy (such as family/sub-family), ecology (distribution and ecological adaptation), morphology (plant characteristics), silviculture (management), and main uses of each species. Other relevant information is given under the sub-heading "Comments". Photographs of some of the species are also included; moreover, references are made to agroforestry-system photographs in other chapters in which the species being profiled appears prominently.

The information has been collated from several sources, mentioned in Section 13.1, as well as from field experience, and is thus of a general nature. For any species, deviations from these general characteristics can be expected under diverse field conditions. Hundreds of MPTs exist in agroforestry systems around the world; only about 50 are included here. These were not selected based on any special criteria other than the relative prominence of the species in the agroforestry systems that are common in one or more geographical regions.

The botanical names of some of the species have changed recently. As much as possible, the present, correct names and the synonyms are given using the ICRAF’s *Agroforestree* database (Orwa et al. 2009), Plant List Version 1.1 (www.theplantlist.org), and the Invasive Species Compendium (CABI 2019). There are such name changes in plant families too: the taxonomy of the family Leguminosae, an important family to which many MPTs belong, also known as Fabaceae, is in a process of transition: Caesalpinioideae, Mimosoideae, and Papilionoideae, the three subfamilies of Leguminosae, are being elevated to the status of families as Caesalpinaceae, Fabaceae or Papilionaceae, and Mimosaceae, respectively. Similarly, Palmaceae, or the palm family, is now correctly known as Arecaceae. Many of the species are known by several local names in different places; because of the multiplicity of these local names, they are not mentioned here.

Acacia mangium Willd.
(Fabaceae; Mimosoideae)

Origin and Distribution: Australia, Papua New Guinea; introduced to several Asian countries.

Ecology: Occurs in moist lowland tropics (1500–3000 mm annual rainfall, from sea level to 800 m altitude) on acidic soils; usually along streams and on well-drained flats and low ridges.

Plant Characteristics: Evergreen single-stemmed tree or shrub; 25–35 m height and 60 cm diameter; erect, stately habit (Figure 13.A.I.1; See Chapter 11, Figure 11.6.2); propagated by seedlings or cuttings; fast growth; N_2 fixing; coppices (only young trees); shade-intolerant.

Main Uses: Germinating seeds cooked and eaten as a vegetable; timber (0.65 sp. gr.); fuelwood and charcoal (4800–4900 kcal kg^{-1}); watershed protection; firebreaks; ornamental; fodder.

Comments: Ability to grow on a wide range of sites makes it popular for reforestation; plantations quickly attain canopy closure, which is ideal for combatting *Imperata* grass; pioneer species.

Figure 13.A.I.1 *Acacia mangium* Unlike most other species of the genus Acacia, *A. mangium* is fast-growing and adapted to humid lowlands of South and Southeast Asia. (Photo: BM Kumar)

Acacia nilotica (L.) Willd. ex Del.
(Fabaceae; Mimosoideae)

Synonyms: *Vachellia nilotica* (L.) P.J.H.Hurter & Mabb.; *Mimosa nilotica* L.

Origin and Distribution: Native to semiarid Africa; introduced to Indian sub-continent.

Ecology: Dry tropics at low altitudes including areas of low and unpredictable rainfall and high temperatures; prefers alluvial soils, but grows well on heavy clay, as well as poor soils.

Plant Characteristics: To 20 m, but usually less; can be a shrub in very unfavorable conditions; flat or umbrella-shaped crown (Figure 13.A.I.2); propagated by direct seeding, seedlings, and root suckers; N_2 fixing; coppices; strong light demander.

Main Uses: Fuelwood and charcoal (sp. gr. 0.67–0.68; calorific value: 4500–4950 kcal kg^{-1}); wood is termite-resistant and is employed for a variety of farm uses; fodder (pods, leaves); tannin and gum; land reclamation.

Comments: Extremely thorny; subject to wood borer attack; thrives under irrigation; requires weeding in early establishment stages. Commonly known as babul or gum arabic tree. Several subspecies have been reported.

Figure 13.A.I.2
Acacia nilotica trees on farmlands in Chattisgarh, Central India, with rice as the understory crop and *Sesamum indicum*, a short-duration (90 days from sowing to harvesting) oilseed crop on the bunds (risers) between plots. The rice is planted in standing water in a puddled field; when the rains subside, the water is drained off. The tree withstands some waterlogging as well as dry conditions. (Photo: PKR Nair)

Acacia senegal (L.) Willd. (The Gum Arabic Tree)
(Fabaceae; Mimosoideae)

Origin and Distribution: Native to Africa (Senegal to Sudan), Pakistan, and India; introduced to Egypt and Australia.

Ecology: Found in dry tropics (200–800 mm rainfall, 8–11 dry months/year) at 100–1700 m altitude (Figure 13.A.I.3); grows on poor soils, but waterlogging not tolerated.

Plant Characteristics: To 13 m, but a shrubby habit is common; many geographical races; propagated by direct seeding and seedlings; competes well with weeds; N_2 fixing; coppices.

Main Uses: Fuelwood (up to 5 m^3 ha^{-1} yr^{-1}); gum arabic; local construction wood; food (seeds); fodder (pods, leaves); erosion control and soil rehabilitation; dune stabilization.

Comments: Four varieties are recognized: *senegal*, *kerensis, rostrata*, and *leiorachis*; major component of agroforestry systems in the geographic region to the south of the Sahara stretching from West Africa to East Africa.

Figure 13.A.I.3 *Acacia senegal*, the gum Arabic tree, a common species on farms and landscapes throughout the drylands of subSaharan Africa. (Photo: ICRAF/World Agroforestry)

Adansonia digitata L. (The African Baobab Tree)
(Bombacaceae)

Synonyms: *A. bahobab* L.; *A. baobab* Gaertn.; *A. integrifolia* Raf.; *A. scutula* Steud.; *A. situla* (Lour.) Spreng.; *A. somalensis* Chiov.; *A. sphaerocarpa* A.Chev.; *A. sulcata* A.Chev.; *Baobabus digitata* (L.) Kuntze; *Ophelus sitularius* Lour.

Origin and Distribution: Widely distributed across continental Africa; exotic ranges include the Caribbean, parts of tropical South America, the Indian subcontinent, and East Asia

Ecology: Occurs in thorny, low altitude woodlands in the arid and semiarid African savannahs (Figure 13.A.I.4); resistant to fire, termite, and drought; prefers a high-water table, but sensitive to waterlogging; mean annual rainfall: 100–1500 mm.

Plant Characteristics: A large, round canopied tree with a swollen trunk, 10–25 m high, 200–600 cm diameter at maturity; initial fast growth; lives for >1000 years; propagated mainly by seeds (need pre-treatment), but stem cuttings and grafts are also common.

Main Uses: Seeds, leaves, roots, flowers, fruit pulp, and bark are edible; leaves eaten fresh or dried are the main source of food and folk medicine in Africa; wood is light but used for handicrafts; firewood; fodder; fiber bark; apiculture; part of African folklore and traditions.

Comments: Pollarded or lopped to stimulate foliage production; several phytochemical constituents with medicinal properties have been identified, including vitamin C, steroids, flavonoids, epicatechin, campesterol, tocopherol, adansonin, and amino acids.

Figure 13.A.I.4 *Adansonia digitata*, the baobab tree, a distinct tree species on the African landscape (Stock photo)

Ailanthus triphysa (Dennst.) Alston (Simaroubaceae)

Synonym: *Ailanthus malabarica* DC.

Origin and Distribution: An Asian and Australian rainforest tree species; occurs in South and Southeast Asia, Southern China, and Australia.

Ecology: Found in the evergreen to semi-evergreen forest margins to 1000 m altitude in the humid tropics with annual rainfall > 2000 mm; light-demanding; well-drained light/sandy soils.

Plant Characteristics: Medium to tall tree; forms a compact crown (Figure 13.A.I.5); attaining a height of 30 m; fast growing; propagation through seeds.

Main Uses: The wood, being light and comparatively soft, is preferred for match manufacture but also used for making boats, sword handles, spear sheaths, paper pulp, fuel, and charcoal. Stem cuttings yield a gum and the bark contains aromatic oils used in medicines and aromatics in India; widely used as live stakes for supporting black pepper (*Piper nigrum*).

Comments: The compact crown and straight and self-pruning, cylindrical bole make it well suited for agroforestry systems.

Related Species: ***Ailanthus excelsa*** Roxb., adapted to drier regions (500 – 2000 mm rainfall)

Figure 13.A.I.5 *Ailanthus triphysa* in Kerala, India. (Photo: BM Kumar)

Albizia lebbeck (L.) Benth.
(Fabaceae; Mimosoideae)

Origin and Distribution: Native to India and Myanmar (Burma); introduced to other parts of Asia, as well as Africa, the Caribbean, and South America.

Ecology: Widely adapted to dry and moist tropics (500–2000 mm rainfall), up to 1600 m altitude on a variety of soils (including saline).

Plant Characteristics: To 30 m; spreading, umbrella-shaped crown (Figure 13.A.I.6); moderately fast growth; propagated by seeds, seedlings, and root suckers; coppices; N_2-fixing.

Main Uses: Fuelwood (high calorific value: 5200 kcal kg^{-1}; 5 m^3 ha^{-1} yr^{-1} produced on 10–15 years rotation); fodder; furniture wood; erosion control.

Comments: Roots close to soil surface; easily damaged by wind; promising species for silvopastoral systems; after establishment, bi-annual pollarding may produce significant biomass.

Related Species

Albizia falcataria (L.) Fosberg: (see ***Paraserianthes*** *falcataria* (L.) Nielson)
Albizia saman (Jacq.) F. Muell (See ***Samanea saman*** (Jacq.) Merr.)

Figure 13.A.I.6
Albizia lebbek (Shirish tree). (Photo: ICRAF/ World Agroforestry)

Alnus acuminata H.B.& K.
(Betulaceae)

Synonym: *A. jorullensis* H.B.K. (also 26 other synonyms).

Origin and Distribution: Native to Central and South America.

Ecology: Cool tropical highlands (2000–3000 m) with 1000–3000 mm annual rainfall on well-drained, fertile soils; neither drought- nor heat-tolerant; a fast-growing pioneer species that regenerates naturally in open, disturbed areas.

Plant Characteristics: To 25 m or more; N_2 fixing; propagated by seed, seedlings, and root cuttings; coppices.

Main Uses: Fuelwood (10–15 m^3 ha^{-1} yr^{-1} in 20-year rotations; calorific value 4600 kcal kg^{-1}); timber (sp. gr. 0.36); watershed protection; soil improvement; silvopastoral systems.

Comments: Competes poorly with weeds during establishment phase; good pasture found under trees.

Related Species

Alnus nepalensis D. Don - Native to the Himalayas, China, and India; introduced to Africa;

Cool tropical highlands (1000–3000 m) with 500–1250 mm annual rainfall; To 30 m (up to 2 m in diameter); fast-growing; N_2 fixing; propagated by seeds and seedlings; fuelwood (sp. gr. 0.32–0.37; calorific value 4357 kcal kg^{-1}); wood for boxes; symbiosis with nitrogen-fixing actinomycetes (*Frankia*); shade tree for large cardamom (*Amomum subulatum*) or *Cinchona* spp. in the Himalayan region (Figure 8.15).

Artocarpus altilis (Parkinson) Fosberg (The Breadfruit Tree)
(Moraceae)

Synonyms: *A. communis* J.R.Forst. & G.Forst. and 12 other names.

Origin and Distribution: Native to New Guinea and possibly the Moluccas (Indonesia) and the Philippines; pan-tropical distribution.

Ecology: Tropical lowlands below 600 m; rainfall 1500–3000 mm; deep, fertile, well-drained soils; requires some shade when young; develops a compact, dense canopy under full sun.

Plant Characteristics: Single trunked tree with spreading, evergreen canopy (Figures 7.23 and 7.54); fast growth under favorable conditions; propagated from root shoots or root cuttings by air-layering branches, or grafting; the plant exhibits great variability, ranging from seedless to true-seeded cultivars.

Main Uses: Fruit a starchy staple; high in carbohydrates and a good source of vitamins and minerals; seeds are high in protein and low in fat; all parts have medicinal value in the Pacific and the Caribbean; wood is lightweight, and flexible; easy to work and for carving; firewood.

Comments: An important component of agroforestry systems associated with many staple and non-staple crops; interplanted with small fruit trees or short-term fruit and vegetable crops; genetically diverse; several named varieties are clonally propagated in the Pacific islands.

Artocarpus heterophyllus Lam. (The Jackfruit Tree)
(Moraceae)

Synonyms: *Artocarpus brasiliensis* Gomez, *A. heterophylla* Lam., *A. maxima* Blanco, *A. philippensis* Lam.,

Origin And Distribution: Native to the rainforests of Malaysia and the Western Ghats of India; common in South and Southeast Asia, the Pacific islands, and parts of Africa.

Ecology: Grows in a wide range of tropical and subtropical conditions; altitude up to1600 m; (mean annual rainfall 1000–2400 mm); prefers well-drained, deep soils; sensitive to waterlogging; tolerates drought (3–4 months); seedlings grow best in 30–50% sunlight.

Plant Characteristics: Medium-sized evergreen tree; 8–25 m tall; fruit is the largest among cultivated plants (Figure 13.A.I.7); dense crown, conical in young and shaded trees; coppices well; propagated by grafts, cuttings and air layering or by seeds, which are recalcitrant.

Main Uses: Fruits are eaten fresh or preserved; nutritious seeds either cooked by boiling or roasted before consumption; fruit pulp and seeds medicinally important; foliage an excellent fodder; medium hardwood (sp. gr. 0.6–0.7) valued as construction wood and lumber; used for making furniture, cabinets and musical instruments; resistant to termite attack.

Comments: One of the most significant components of tropical homegardens; being open pollinated, genetic variability is high.

Figure 13.A.I.7 *Artocarpus heterophyllus*: Stock photo

Azadirachta indica Adr. Juss. (The Neem Tree) (Meliaceae)

Origin and Distribution: South Asia; introduced to many parts of Africa.

Ecology: Dryland, low altitude tropics (50–1500 m, 130–1150 mm rainfall); on variable soils; does not tolerate waterlogging or salinity.

Plant Characteristics: To 15 m; deep-rooted; evergreen except in periods of extreme drought (Figure 13.A.I.8); coppices well; early growth from coppice is faster than growth from seedlings; propagated by seeds, seedlings.

Main Uses: Fuelwood (sp. gr. 0.68, high calorific value 6.94 kcal g^{-1}); construction wood and lumber; windbreak; oil (seeds); shade; soil improvement (leaves, seed residue after oil extraction); industrial chemicals; insect repellant and anti-pest properties; seeds and leaves contain azadirachtin, which is the principal active compound of neem-based pesticides.

Comments: Seeds quickly lose viability; can become a weed; tolerates long dry periods; seedlings compete poorly with weeds.

Figure 13.A.I.8 *Azadirachta indica* (the neem tree) in Mali, West Africa. (Photo: PKR Nair)

Bactris gasipaes Kunth.
Peach palm (English); Pejibaye (Spanish); *Pupunha* (Portuguese)
(Arecaceae)

Synonyms: *Guilielma speciosa* Martius, *G. gasipaes* (Kunth) Bailey, *G. utilis* Oersted

Origin and Distribution: Central and South America

Ecology: Adapted to a wide range of ecological conditions including acid soils; most productive on relatively deep, fertile, well-drained soils at low to middle altitudes (<800 m); sensitive to waterlogged soils; can withstand relatively short dry seasons (3–4 months), if soils are not excessively sandy.

Plant Characteristics: Typically, multi-stemmed (cespitose), although single-stemmed plants do occur (Figure 13.A.I.9); propagated by seeds, which are recalcitrant; asexually through offshoots and tissue culture, which are yet to develop on commercial lines; rapid juvenile growth.

Main Uses: Provides several nutritious staple foods; fruit pulp for direct consumption; flour for infant formula and baked goods; cooking oil; livestock feed; boiled mesocarp, with various seasonings, is a popular *hors d'œuvre*; heart-of-palm is an important commercial product; wood is hard and useful for construction.

Comments: The only palm species with domesticated populations in the Neotropics; cultivated peach palm is genetically diverse with many landraces; a popular and promising tree for agroforestry systems.

Figure 13.A.I.9 *Bactris gasipaes* The peach palm (Pejibaye in Spanish and *pupunha* in Portuguese) in Belém, Pa, Brazil. (Photo: Charles Clement)

Borassus aethiopum C. Martius
(Arecaceae)

Origin and Distribution: Native to Tropical Africa; introduced to India and Southeast Asia.

Ecology: Found in the subhumid to semiarid tropics (500–1150 mm annual rainfall) at altitudes up to 600 m on medium, loamy to heavy, clayey, soils; can withstand saline soils.

Plant Characteristics: To 20 m; single-stemmed, straight, erect habit; evergreen; deep rooting; light-demanding; fire resistant; tolerates high temperatures; propagated by direct seeding and seedlings; seeds are recalcitrant.

Main Uses: Fodder; edible leaves, fruits, and seeds; beverages from fruit pulp and milk; palm wine; oil; fuelwood and charcoal; poles and posts; timber for house construction; medicine; fiber; packaging material; cosmetics; intercropped with millets, peanut (*Arachis hypogaea*).

Comments: Usually found in areas with a high water-table; wood is highly resistant to termite.

Related Species:
Borassus flabellifer L. (The Palmyra Palm; Figure 13.A.I.10). Native to the Indian subcontinent and Southeast Asia. Dry to moist tropical and subtropical climates, up to 800 m elevation. Adapted to a wide range of rainfall (250–5000 mm) and temperature conditions (0°–45 °C). Tall, single-stemmed evergreen palm, up to 30 m in height. As in coconut, tapping the palmyra palm inflorescence yields a nutritious sweet sap (toddy) that yields crude sugar (gur or jaggery), molasses, palm candy, and vinegar. Young solid or gelatinous endosperm of the seeds eaten fresh or in syrup; immature fruits pickled; all parts are important in folk medicines. Leaves used as thatch and for basket and mat making; A subsistence crop of the smallholders; intercropped as well as planted as a windbreak in the plains; used as a natural shelter by birds and bats in India.

Figure 13.A.I.10 The palmyra (*Borassus flabellifer*) palms in combination with various trees in Tamil Nadu, India. (Photo: BM Kumar)

Bursera simaruba (L.) Sarg.
(Burseraceae)

Synonyms: *Bursera gummifera* L. and 12 others.

Origin and Distribution: Native to tropical America; occurs in South and Central America, and to the north through the Caribbean to Florida.

Ecology: Occurs in dry forests, but sometimes in wetter forests; altitudinal range up to 1000 m; mean annual temperature 18–25 °C; mean annual rainfall 800–3000 mm; prefers well-drained dry or moist soil with neutral and alkaline pH; but tolerates very alkaline and saline soils.

Plant Characteristics: Medium-sized, deciduous tree; 18–30 m tall; large, spreading, crooked branches; drought-tolerant; propagated by seed.

Main Uses: Leaves used as a tea substitute; branches are cut for cattle fodder; wood used as firewood or charcoal; also used for making plywood, tools, match sticks, toothpicks, cabinets, decorative articles and the like; yields balsam resin (used in South America as incense); bark medicinally important; ornamental tree; living fence.

Comments: Commonly known as gum tree or turpentine tree; the aromatic resin is a natural insect repellent.

Calliandra calothyrsus Meissner
(Fabaceae; Mimosoideae)

Origin and Distribution: Native to Central and South America; introduced in Indonesia, the Philippines, parts of Africa, the Caribbean and South Asia.

Ecology: Occurs in moist tropics (2000–4000 mm annual rainfall, but can withstand droughts) at altitudes between 250–1800 m on a variety of soils (including infertile as well as clay-type soils); prefers light textured, slightly acidic soils; does not tolerate waterlogged and alkaline soils.

Plant Characteristics: To 10 m; multi-stemmed shrub (see Figures 9.18, 11.5); N_2 fixing; coppices; established by direct seeding or seedlings; fast growing, easy to regenerate and manage.

Main Uses: Fuelwood (5–20 m^3 ha^{-1} yr^{-1}); fodder (but high tannin may cause low digestibility); green manure; honey production; to rehabilitate erosion-prone areas.

Comments: Competes well with weeds; an aggressive colonizer on disturbed sites; poor seed production (in some situations); insect pests attack flowers.

Casuarina equisetifolia Forst. & Forst. (Casuarinaceae)

Synonym: *Casuarina littorea* L.

Origin and Distribution: Native to Australia; introduced to India, Pakistan, East, Central, and West Africa, West Indies, subtropical U.S., the Caribbean, and Central America.

Ecology: Native to warm tropical coastal areas as well as semiarid regions (0–600 m, 1000–5000 mm annual rainfall); usually on sandy soils; tolerates both calcareous and slightly alkaline soils.

Plant Characteristics: To 35 m; N_2 fixing (through association with actinomycetes); propagated by seedlings; rooted cuttings; coppices (only in some ideotypes); fast-growing (Figure 13.A.I.11).

Main Uses: Fuelwood and charcoal (sp. gr. 1.0, one of the best in the world; calorific value 5000 kcal kg^{-1}); windbreak; timber for post wood; erosion control; dune stabilization.

Comments: Can withstand waterlogging for a short period; wood yield 75–200 t ha^{-1} on a rotation of 7–10 years with a 2 m-spacing between plants; salt-tolerant and wind-resistant; adaptable to moderately poor soils.

Figure 13.A.I.11 *Casuarina equisetifolia* in Tamil Nadu, India. (Photo: BM Kumar)

Related Species

Casuarina cunninghamiana Miq. Native to Australia; introduced to Africa, Argentina, the U.S., Israel, and China. Occurs in the cool tropics and subtropical areas (600–1100 mm annual rainfall) on acidic soils at elevations up to 800 m. To 35 m tall; relatively cold-tolerant; N_2 fixing (actinorhizal) with profuse nodulation involving *Frankia*, propagated by seedlings and root suckers; extensive, shallow roots; fast-growing. Fuelwood (sp. gr. 0.7; calorific value of *ca.* 5,000 kcal kg^{-1}); timber is durable and useful for flooring; shade; riverbank stabilization; windbreak. Can become a weed especially along canals and watercourses (declared as a weed in Florida); not adaptable to calcareous soils; susceptible to browsing damage.

Cedrela odorata L. (The Spanish Cedar) (Meliaceae)

Origin and Distribution: Native to Central and South America; introduced to the Caribbean, and parts of Africa and Asia; widely grown as a timber species in the Neotropics.

Ecology: Adapted to the humid tropics (1000–3700 mm annual rainfall) at altitudes up to1900 m on medium, loamy to heavy, clayey, well-drained, deep soils with an acid to neutral pH; component of both primary and secondary evergreen to semi-deciduous lowland or lower montane rainforest in its native range; light-demanding and drought-hardy.

Plant Characteristics: Large tree (up to 60 m tall) with an average of about 25 m; erect, single-stemmed, straight stem; evergreen; spreading canopy; shallow lateral roots; sometimes forms buttresses; fast-growing; does not tolerate water-logging or flooding; can be propagated by direct sowing and seedlings.

Main Uses: Timber for furniture and house construction; turnery; apiculture; fuelwood; produces attractively patterned veneer; medicinally important (bark, leaves, trunk, fruit, seeds); used for shade and as a windbreak in courtyard gardens and cacao and coffee plantations.

Comments: Included in the IUCN Red List of vulnerable species; susceptible to insect damage; harvested wood is resistant to termites; tolerates seasonally waterlogged sites.

Ceiba pentandra (L.) Gaertn. (The Kapok or Silk-cotton Tree)
(Bombacaceae)

Origin and Distribution: Found pantropically; origin believed to be Central America.

Ecology: Found in the humid and subhumid tropics (750–2500 mm annual rainfall) at altitudes of 0–1600 m on light, sandy to medium, loamy, well-drained soils with a neutral pH; a pioneer species; mostly occurs in secondary forests.

Plant Characteristics: Tall, deciduous tree with height to 60 m with an average of 30 m; single-stemmed with an open canopy (Figure 13.A.I.12); buttressed; thorny; deciduous during the dry season; propagated by seedlings and cuttings; light demanding; moderately drought resistant; fast growth (up to 1.2 m yr^{-1}) for first 10 years; susceptible to wind damage.

Main Uses: Fiber or cotton from seed capsules; edible leaves; fodder; apiculture; medicine; cosmetics; the pressed cake is a cattle feed containing about 26% protein. The wood is very light, with a specific gravity of 0.25 g/cc; suitable for matchwood, light plywood containers, packing cases, fuelwood, etc.

Comments: The floss derived from the inner fruit wall yields the kapok fiber – traditionally used for stuffing cushions, pillows, and mattresses, and for insulation, and as an absorbent material and tinder.

Figure 13.A.I.12 *Ceiba petandra*, the kapok or silk-cotton tree. (Photo: BM Kumar)

Cordia alliodora (Ruiz *et* Pavon) Cham. (Boraginaceae)

Origin and Distribution: Native to Central America.

Ecology: A pioneer species found in a wide range of habitats; common in drier areas; occurs in moist tropical lowlands and midlands (up to 800 m, 750–2000 mm annual rainfall) on deep, well-drained, medium-textured soils; a strong, light-demanding species.

Plant Characteristics: To 30 m; deciduous; light canopy (coffee, cacao intercropped in Costa Rica; see Figure 8.6); large superficial, spreading roots (deep when soil conditions are favorable); wind-resistant and shade-intolerant; propagated by direct seeding, seedlings, and root suckers; coppices.

Main Uses: Timber; poles; shade tree for crops (cacao, coffee); soil improvement; fuelwood (sp. gr. 0.29–0.70); food (fruits); ornamental.

Comments: A renowned timber species; permits understory crops; attacked by canker-causing rust disease on poor sites; low seed viability (1–2 months only); silviculture well developed; wood is resistant to decay and termites.

Dacryodes edulis (G. Don.) H. J. Lam. (Burseraceae)

Synonyms: *Canarium edule* (G.Don) Hook.f., *C. mansfeldianum* Engl., *Pachylobus edulis* G. Don., *P. saphu* (Engl.) Engl.

Origin and Distribution: Africa; introduced to Malaysia

Ecology: Occurs in the evergreen rainforest, gallery forest and marshes; adapts well to differences in day length, temperature, rainfall, and soils; prefers altitude up to 1000 m, mean annual precipitation of 1400–4000 mm, and mean annual temperature of 23–25 °C.

Plant Characteristics: A medium-sized, evergreen tree, 18–40 m tall in the forest but about 12 m in plantations; deep, dense crown; short bole; 50–170 cm in diameter; shade-loving.

Main Uses: Pulpy, pericarp eaten either raw or cooked; fruit pulp rich in vitamins and contains a range of amino acids, yields about 48% edible oil; kernel fed to sheep and goats (about 3.3% protein); wood for making tool handles, suitable for carpentry; bark and leaves medicinally important; suited for intercropping.

Comments: Known as African pear and African plum; planted in southern Nigeria, Cameroon, and the Democratic Republic of Congo for its nutritious fruit.

Dalbergia sissoo Roxb. ex DC
(Fabaceae; Papilionoideae)

Origin and Distribution: Native to the Himalayan foothills (India, Pakistan, and Nepal); introduced to the USA and the western and eastern parts of Africa.

Ecology: Occurs in the subtropics to tropics on semiarid sites and neutral to acid soils with good drainage; altitude up to 1500 m; mean annual temperature –4 to 45 °C; rainfall 500–4500 mm.

Plant Characteristics: A medium to large-sized deciduous tree, up to 30 m height and 80 cm diameter at breast height (under favorable conditions); wide-spreading and thin crown; N_2 fixing; light-demanding; coppices; fast-growing; frost-resistant and drought hardy; propagated by direct seeding, seedlings, stump sprouts, root suckers, and branch cuttings.

Main Uses: Fuelwood (sp. gr. 0.83, 5–8 m^3 ha^{-1} yr^{-1}; calorific value 4.9–5.2 kcal g^{-1}); sawn timber; fodder; soil erosion control; ornamental; heartwood very hard and close-grained; used for high-quality furniture, cabinets, decorative veneer, carving, engraving, tool handles and sporting goods; heartwood yields light brown, viscous, non-drying fixed oil (5.35%), suitable as a lubricant for heavy machinery; planted in homegardens; medicinally important.

Comments: Termites attack young plants; seedlings do not compete well with weeds (weeding for 2-3 years required); browsed heavily by wild animals.

Erythrina poeppigiana (Walp.) Cook
(Fabaceae; Papilionoideae)

Synonyms: *Erythrina micropteryx* Poeppig ex Walpers, *Micropteryx poeppigiana* Walpers.

Origin and Distribution: Latin America from Costa Rica to Bolivia; introduced to West Indies.

Ecology: Native to the riverine and upland forests of the Amazon and Orinoco Basins. Cultivated and naturalized trees are found at elevations up to 2000 m in dry to subhumid tropics (1500–4000 mm annual rainfall, up to 6-month dry seasons) at medium altitudes to highlands.

Plant Characteristics: To 40 m; fast growth; N_2 fixing (abundantly nodulated with *Bradyrhizobium*); coppices; propagated by direct seeding, seedlings, and cuttings; can tolerate drought and temporary waterlogging; but cannot grow under shade.

Main Uses: Shade tree for coffee (See Figure 8.4) and cacao; support plant for betel, black pepper, vanilla, and grape vines; live fences (cuttings easily root); ornamental; soil fertility improvement; fodder; green manure (8–12 Mg ha^{-1} yr^{-1} produced); alley cropping; live fencing.

Comments: One of the most commonly planted shade trees for cacao and coffee, and support for black pepper in Central America; increases soil fertility; good coppicing ability.

Related Species (used commonly in agroforestry systems):
E. *berteroana* in Central America, and ***E. indica*** in India.

Euterpe oleracea [The Açaí (Assai) palm] (Arecaceae)

Synonym: *Erythrina micropteryx* Poeppig ex Walpers, *Micropteryx poeppigiana* Walpers.

Origin and Distribution: Brazil and the northern parts of South America.

Ecology: Native to Brazil, Ecuador, Venezuela, Colombia, Guyana, mainly in swamps and floodplains.

Plant Characteristics (Figure 13.A.I.13)**:** A tall, slender palm growing to more than 25 m. To 40 m; seed-propagated; bears fruit all around the year; usually two harvests per year, one between January and June and the other between August and December

Main Uses: Cultivated for its fruit (açaí berries), hearts of palm (a vegetable), leaves, and trunk wood. With the extension of consumption of the (small, round, and black-purple) fruit from the floodplain areas to urban centers and its promotion as a health food since the 1990s, its global demand has expanded rapidly.

Comments: Popular as a fruit, fruit supplement; the "açaí bowl" a combination of frozen açaí puree or açaí powder with other ingredients such as nut milk, fruit juice, fruit, nuts, oatmeal, and a sweetener has become a popular dessert in North America.

Figure 13.A.I.13 *Euterpe oleracea* [The Açaí (Assai) palm) in Belém, Pa, Brazil]. (Photo: Charles Clement)

Faidherbia albida Del. A. Chev.
(Fabaceae; Mimosoideae)

Synonym: *Acacia albida* Del., *Acacia albida* var. *senegalensis* Benth., *Acacia gyrocarpa* Hochst. ex A. Rich., *Acacia mossambicensis* Bolle, *Acacia saccharata* Benth.,

Origin and Distribution: Widespread in dry tropical Africa into the Middle East and Arabia. Introduced into India, Pakistan, Nepal and, in the Western Hemisphere, Peru.

Ecology: Found in arid and semiarid regions (400–900 mm annual rainfall) at altitudes of 100–2500 m on variable soils, but loamy and sandy types preferred.

Plant Characteristics (See Figures 9.7–9.10)**:** To 20 m with wide, spreading crown; leaves shed during rainy season and retained during the dry season (West Africa). Propagated by direct seeding (after scarification), seedlings, root suckers; coppices well; N_2 fixing.

Main Uses: Forage (pods, foliage); shade; fencing (cut thorny branches); tannin; medicine.

Comments: Slow early growth; considerable stand variability; soil fertility improvement with 5–76% increases in crop yields under trees reported. The remarkable phenological characteristic of the trees shedding their leaves in the rainy season and the leaves reappearing at the beginning of the dry season is acclaimed as the "Albida Effect" in agroforestry literature. This special feature, however, is not conspicuously expressed on trees growing outside the West African Sahel.

Flemingia macrophylla (Willd.) Merr.
(Fabaceae; Papilionoideae)

Synonyms: *F. congesta* Roxb. ex Ait.f.; 26 other Latin names.

Origin and Distribution: Native to South and Southeast Asia; introduced to parts of Africa and tropical America; has long been used – and thus become naturalized – throughout the East-, Central-, and West Africa, Hawaii and North Australia for soil improvement.

Ecology: Found in the sub-humid and humid tropics at low to medium altitudes on sites with 1000–2000 mm annual rainfall (including up to 4 month dry seasons) on a wide range of soils; capable of surviving on poorly drained soils with waterlogging.

Plant Characteristics: Woody, tussock-forming shrub, erect or prostrate, 3 – 4 m tall, with a spreading crown; fast growing; deep-rooted; N_2 fixing; tolerant of light shade; coppicing ability; propagated by direct seeding or seedlings.

Main Uses: Fodder; support for climbing plants; soil erosion control (in contour hedgerows); green manure; cover crop; dye; traditional medicine; used for agroforestry in Nepal and Bhutan.

Comments: After becoming established (3–4 months), the plant can out-compete many weeds; weeding during the first 2 months necessary. Large-scale plantations have been established in south China and India for lac insect (*Kerria lacca*) breeding; potentially invasive.

Gliricidia sepium (Jacq.) Walp.
(Fabaceae; Papilionoideae)

Synonyms: *Galedupa pungam* Blanco, *Gliricidia lambii* Fernald, *G. maculata* (Kunth) Walp., *Robinia maculata* Kunth, *R. sepium* Jacq., *R. variegata* Schltdl, and a few others.

Origin and Distribution: Native to Mexico and Central America; extensively introduced to West Indies, Africa, Southeast and South Asia and the Pacific islands.

Ecology: Grows in dry to humid tropics (600–3000 mm annual rainfall) at 500–1600 m on moist to dry, and even saline soils; tolerates brief waterlogging.

Plant Characteristics: To 10 m; medium-sized tree; fast growth; N_2 fixing; coppices; easily propagated by direct seeding, seedlings, and cuttings.

Main Uses: Shade for cacao, coffee, vanilla, and tea; green manure; fodder (mainly for cattle); honey production; live fences; ornamental; alley cropping; medicinal (leaves); grown in hedges; on terraces to control soil erosion; soil fertility improvement; wood is often utilized as firewood and for charcoal making (density: 47–75 g cm^{-3}; calorific value: 4900 kcal kg^{-1}).

Comments: One of the most widely planted agroforestry species (Figures 6.1, 6.2, 11.10). Popular as a shade tree for cacao in Central America and known as the *Madre de cacao* (Spanish for Mother of cacao); "Quick stick" in the Caribbean islands, where one-year old shoots planted along with yams establish roots fast and sprout vigorously to and provide support for trailing the yam shoots.

Grevillea robusta A. Cunn. ex R. Br.
(Proteaceae)

Synonyms: *G. robusta* var. *compacta* auct., *G. robusta* var. *forsteri* L.H.Bailey,

Origin and Distribution: Native to Australia; introduced to the warm temperate, subtropical and tropical highland regions around the world; widely planted in South Asia, Central and South America and many countries in Africa.

Ecology: Found in humid to subhumid climates (400–1500 m annual rainfall with up to 6–8month dry seasons) from sea level to 2300 m on a wide range of soils, but deep soils preferred.

Plant Characteristics: Erect, single-stemmed tree reaching 20–30 m tall and 80 cm in stem diameter; crown is conical and symmetrical; fast growth; deep-rooted; pollards well but does not coppice well; propagated by direct seeding or seedlings.

Main Uses: Shade tree for coffee and tea (See Figures 8.7, 8.19); fuelwood (sp. gr. 0.57, 217 m^3 ha^{-1} from 14-year-old plantation); mulch; ornamental; honey production; soil improver; sawn timber of medium strength for furniture, packing cases, flooring, paneling; poles for house-construction, scaffolding; firewood and charcoal; calorific value of heartwood 4950 kcal kg^{-1}.

Comments: Low seed viability unless refrigrated; can become a weed due to vigorous natural regeneration from seed; does not tolerate waterlogging.

Grewia optiva J.R. Drumm. ex Burret
(Tiliaceae)

Synonyms: *Grewia oppositifolia* Buch.-Ham. ex Roxb.

Origin and Distribution: Native to Indian subcontinent.

Ecology: Tree of the subtropical climate found in highland subhumid regions with bimodal, monsoonal rainfall (1700–2200 mm annually); altitude up to 2000 m; medium, loamy to heavy, clayey, well-drained soils with a neutral to alkaline pH.

Plant Characteristics: Erect, straight habit; single to multi-stemmed with a dense canopy; deep rooting; height ranges from 7–10 m; regenerated by seedlings, coppice from stumps, and direct seeding.

Main Uses: Edible pods and fruits; fodder; furniture; wood for construction; fiber; charcoal; often planted in hedges and field boundaries; suitable for intercropping.

Comments: Light-demanding; drought sensitive; intolerant of fire and strongly acidic soils; susceptible to browsing damage; moderately frost resistant; tolerates strongly alkaline soils; can withstand heavy lopping or pollarding.

Inga edulis Mart.
(Fabaceae; Mimosoideae)

Synonyms: *Feuilleea edulis* (Mart.) Kuntze and seven other names

Origin and Distribution: Native to tropical South America.

Ecology: Generally associated with warm, lowland, wet tropics; remarkably resistant to drought and cold; to1600 m altitude; mean annual rainfall 1200 mm; tolerant to acid and poor soils.

Plant Characteristics: Evergreen fast-growing tree; to 25 m tall; light-demanding; nitrogen fixing; propagation by seeds; seeds are recalcitrant and sometimes begin to germinate in the pod.

Main Uses: Food; fodder (pigs eat seeds when hungry, and cattle will even eat whole pods and leaves); timber; firewood (high calorific value and little smoke); shade tree for perennial crops (mainly coffee and cacao); soil improver; controls soil erosion.

Comments: Commonly known as ice cream bean tree; useful for the smallholder's woodlot and a useful bush-fallow species.

Related Species common in agroforestry systems in Central and South America

Inga jinicuil G. Don
Inga vera Willd. ssp. *vera*

Juglans nigra L. (Black Walnut) (Juglandaceae)

Synonyms: *Wallia nigra* (L.) Alef.

Origin and Distribution: Native range is Eastern United States but widely planted outside of its natural range and can be found all over North America.

Ecology: Prefers moist, organically rich, well-drained soils; occurs in association with other hardwoods; grows best in areas with an annual precipitation from 300 to 1300 mm, an annual temperature in the range of 7 to 19 °C and soils of pH from 4.9 to 8.2.

Plant Characteristics (See Figures 10.1, 10.15)**:** Large deciduous tree; to 30 m tall; fast growth; propagated through seeds or through grafts; shade intolerant; not frost tender; well adapted to fire.

Main Uses: Most popular wood used for fabricating solid and veneer furniture; wood very ornamental, heavy, hard, strong, close-grained, durable; seed eaten raw or cooked; high nutritional value; used in several dishes; an excellent dessert nut; seed yields an edible oil; the tree yields a sweet sap that can be drunk or concentrated into syrup or sugar; bark and leaves medicinally important; suitable for interplanting or multicropping.

Comments: Long recognized as one of the most valuable North American trees; produces a toxin called juglone with allelopathic effects. Several walnut hybrids (e.g., *Juglans nigra* x *J. regia* and *J. major* x *J. regia*) have been planted into existing woodlands in Europe.

Juglans regia L. (English or Persian Walnut) (Juglandaceae)

Synonyms: *J. duclouxiana* Dode, *J. orientis* Dode, *J. sinensis* (C. DC.) Dode

Origin and Distribution: Originated in the region from Eastern Balkans to the Himalayas; cultivated in the temperate regions; sometimes hybridized with black walnut (*J. nigra*).

Ecology: Requires moist, organically rich, well-drained soils with pH values between 6 and 7.5; intolerant to shade; sensitive to competition.

Plant Characteristics: Large, long-living deciduous tree; height up to 45 m; light-demanding; propagated by seeds or vegetatively through cuttings, grafting, or layering.

Main Uses: Highly valued for its nutritional seeds (walnuts) and timber; the kernel is consumed, fresh or toasted, alone or mixed with other products; fruits yield oil rich in polyunsaturated fatty acids, tocopherols, and phytosterols, used in paints and in soap-making; high-quality timber used for making furniture and veneer; bark and leaves have medicinal values; tannins extracted; leaves contain juglone with pesticidal and herbicidal properties.

Comments: Fruits, leaves, and alcoholic products from green fruits have antioxidant potential.

Khaya ivorensis A. Chev. (African mahogany) (Meliaceae)

Synonyms: *K. caudata* Stapf ex Hutch. & Dalziel; *K. klainei* Pierre ex Pellegr.

Origin and Distribution: Native range from coastal West Africa, Cote d'Ivoire through Ghana and southern Nigeria to Cameroon; introduced to Fiji, Indonesia, Malaysia.

Ecology: A plant of moist tropical lowland areas; mostly in rainforest; altitude up to 450 m; mean annual temperature 24–27 °C and rainfall 1600–2500 mm; prefers wet alluvial soils.

Plant Characteristics: Very large evergreen tree, deciduous in drier climates; 40–50 m tall and up to 2 m dbh (diameter at breast height); straight, unbranched bole up to 30 m; well-developed plank buttresses; grows very quickly; mainly seed propagated; also by cuttings; light-demanding.

Main Uses: Wood is durable (mean specific gravity 0.53 g m^{-3}) and of high market value; used for high-quality cabinetwork, furniture, and expensive interior finishing; bitter bark is medicinal; soil improver.

Comments: Planted as mixed species stands with close spacing; sole stands are rarely established because of insect damage; "vulnerable"' as per the IUCN Red list.

Related Species

Khaya senegalensis (Desr.) A.Juss. Moist African tropics (Senegal to Uganda), medium-sized, popular, hard timber; leaves relished by cattle and camels; vulnerable as per IUCN Red List.

Leucaena leucocephala (Lam.) De Wit (Fabaceae; Mimosoideae)

Origin and Distribution: Native to Central America and Mexico; introduced to much of South and Southeast Asia, Africa, South America, and the Caribbean.

Ecology: Occurs in lowland dry to humid tropics (below 500 m, 600–1700 mm annual rainfall) on neutral to alkaline soils but not waterlogged sites; sea level to 1800 m altitude.

Plant Characteristics: To 18 m (shrubby and arboreal varieties known); N_2 fixing; deep-rooted; coppices very well; prolific seeder and seeds germinate rapidly; propagated by direct seeding, seedlings; fast-growing.

Main Uses: Fuelwood (sp. gr. 0.55, 24–100 m^3 ha^{-1} yr^{-1}); nurse tree; fodder; small construction wood and pulpwood; some food use (pods, seeds, leaves); energy plantations; alley cropping.

Comments: Possibly the most studied and mentioned species in tropical agroforestry. The fodder is relished by cattle (Figure 13.A.I.14; See also Figures 6.3, 6.7, 18.10), but the leaves contain an alkaloid (mimosine) which may be mildly toxic to cattle if fed on it a sole diet for long periods; usually mixed with grasses to alleviate the problem.

Related Species

Leucaean diversifolia, another species used in agroforestry systems, though to a less extent, is adapted to tropical highlands; has been used in breeding programs with *L. leucocephala*.

Figure 13.A.I.14 Cattle browsing the new shoots of *Leucaena leucocephala* in the height of the dry season when fodder scarcity is at its peak, in Queensland, Australia. (Photo: Vimala Nair)

Madhuca longifolia (Roxb.) A.Chev. (Sapotaceae)

Synonyms: *M. indica* J.F. Gmel., *M. latifolia* (Roxb.) J.F. Macbr. (and a few other names)

Origin and Distribution: Indigenous to India, Sri Lanka, Nepal, Myanmar.

Ecology: A plant of the subtropics to the hot tropics; elevations up to 1200 m; mean annual rainfall 550–1500 mm; temperature 2–46 °C; common in deciduous forests and dry sal (*Shorea robusta*) forests; prefers deep loamy or sandy-loam soil with good drainage.

Plant Characteristics: A deciduous tree about 15 m tall; large, spreading, rounded crown; drought resistant; propagated by direct seeding, frost resistant; requires full light.

Main Uses: Edible flowers, fruits, leaves and oil; the fragrant fleshy flowers are eaten raw or cooked; flowers are also used to brew an alcoholic beverage; seed yields a low-quality oil used in making of soap and candles; bark yields tannin; seed oil are medicinally important; durable and heavy wood (929 kg m^{-3}) used for house construction, furniture and as a fuel; soil improver; soil reclamation and erosion control.

Comments: Commonly known as *Mahua* or butter tree; cultivated or harvested in the wild in Southern Asia.

Melia azedarach L.
(Meliaceae)

Origin and Distribution: Native to Indian subcontinent; introduced to the Middle East, West Indies, southern U.S., Mexico, Argentina, Brazil, and parts of West and East Africa and Southeast Asia.

Ecology: Occurs in low to midlands (up to 2000 m) on sites with 600–1000 mm of annual rainfall on variable soils.

Plant Characteristics (Figure 13.A.I.15)**:** To 30 m; fast growth; short-lived (20–30 years); coppices; shade-intolerant; propagated by root suckers, direct seeding, and seedlings; generally deciduous, but evergreen in the humid tropics.

Main Uses: Fuelwood (sp. gr. 0.66); wood for furniture, plywood, and boxes; insecticide and repellent (leaves, dried fruit); fodder (leaves for goats); ornamental; a wide range of medicinal applications; widely planted as a shade tree in coffee and abaca (*Musa textilis*) plantations.

Comments: Known as Persian lilac; susceptible to wind damage; drought-tolerant; bruised bark and leaves as a fish poison.

Figure 13.A.I.15 *Melia azedarach*. (Photo: BM Kumar)

Mimosa scabrella Benth.
(Fabaceae; Mimosoideae)

Synonyms: *M. bracaatinga* Hoehne,

Origin and Distribution: Native to South and southeastern Brazil, Northeast Argentina; introduced into Central America and East Africa.

Ecology: Grows at mid-elevations in the cool tropical and subtropical regions (prefers annual rainfall > 1000 mm) on a wide range of well-drained soils; tolerates strongly acid soils with high aluminum content; does not tolerate waterlogging.

Plant Characteristics: To 12 m; thornless; slender; fast-growing; shrubby varieties also exist; N_2 fixing; coppices; propagated by direct seeding, seedlings.

Main Uses: Fuelwood; pulpwood; ornamental; green manure; shade for coffee; soil improver; live fence; heartwood is hard, moderately heavy, specific gravity from 450 to 670 kg m^{-3}, used for lumber.

Comments: Flourishes at 2400 m in Guatemala; before the advent of the diesel locomotive, *M. scabrella* wood was grown to fuel railroads in parts of Brazil.

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Moringa oleifera Lam.
(Moringaceae)

Synonyms: *Guilandina moringa* L., *Hyperanthera moringa* (L.) Vahl, *M. moringa* (L.) Millsp., *M. pterygosperma* Gaertn., *M. zeylanica* Burmann

Origin and Distribution: Native to India and Arabia; now pantropical.

Ecology: Occurs in the lowland tropics (0–750 m, 760–2250 mm annual rainfall) on well-drained, deep soils (pH 5–7 preferred).

Plant Characteristics (Figure 13.A.I.16)**:** To 12 m; fast growth; open crown; coppices; propagated by direct seeding, cuttings.

Main Uses: Food (pods when young, leaves, roots, flowers); fodder (leaves); honey production; medicine (bark, roots, leaves); water purification (seeds); soap (seeds); industrial lubricant.

Comments: Competes well with weeds (allelopathic effects suggested); waterlogging not tolerated. Popular in agroforestry (homegarden) systems.

Figure 13.A.I.16 *Moringa oleifera* in Taiwan. (Photo: Manny Palada)

Paraserianthes falcataria (L.) Nielson (Fabaceae; Mimosoideae)

Synonym: *Albizia falcataria* (L.) Fosberg., *Falcataria moluccana* (Miq.) Barneby & J.W. Grimes.

Origin and Distribution: Native to South and Southeast Asia, and the Pacific islands.

Ecology: Found in moist tropics without dry seasons (1000–4500 mm annual rainfall) at 800–1500 m on well-drained soils; a pioneer species, sensitive to fire.

Plant Characteristics: To 45 m; umbrella-shaped crown when grown in the open; fast growth (15 m in 3 years); propagated by seeds (after scarification) and seedlings; N_2 fixing; coppices.

Main Uses: Pulpwood (soft wood with 0.33 sp. gr.); moldings; boxes; soil improvement; fuelwood (but quality is poor).

Comments: Subject to wind damage; can aggravate soil erosion; yields 39–50 m^3 ha^{-1} yr^{-1} of wood on a 10-year rotation cycle; competes well with weeds.

Parkia biglobosa (Jacq.) R. Br. ex G. Don f. (Fabaceae; Mimosoideae)

Origin and Distribution: Native to West Africa; widespread in the Caribbean.

Ecology: Occurs in semiarid to subhumid lowlands (0–300 m; 400–1500 mm annual rainfall) on acid soils; prefers well-drained, deep soils, but also found on shallow soils, and thick laterites.

Plant Characteristics (Figure 13.A.I.17)**:** To 20 m; deciduous; dense, spreading crown; N_2 fixing; coppices; propagated by direct seeding, seedlings.

Main Uses: Timber (sp. gr.: 0.58–0.64); fuelwood; condiment (crushed, fermented pods); fodder (pods, but high tannin); fish poison (fruit husks and bark); medicinal; shade.

Comments: Drought-tolerant (3–7 months dry season) because of its deep taproot system and an ability to restrict transpiration.

Figure 13.A.I.17 *Parkia biglobosa* with crops underneath, in Mali. (Photo: PKR Nair)

Parkinsonia aculeata L. (Fabaceae; Caesalpinoideae)

Synonym: *P. thornberi* M.E.Jones

Origin and Distribution: Native to southwestern U.S., through Mexico and Central America to South America; introduced to Hawaii, South Africa, East Africa, India, Jamaica, and Israel.

Ecology: Grows in widely disparate climates, from dry to humid tropics (200–1000 mm annual rainfall) and in the subtropics at altitudes below 1300 m on various soils; tolerant to drought, waterlogging and salinity.

Plant Characteristics: A small, spiny tree 4–10 m high, with a short and often crooked trunk up to 40 cm in diameter; spreading habit; fast growth; coppices; propagated by root suckers, cuttings, direct seeding, and seedlings.

Main Uses: Fuelwood; fodder (leaves, pods); food (pods); ornamental; apiculture; medicinal (leaf, fruit and stem); erosion control; live fences.

Comments: Not an N_2 fixer; seedlings respond to fertilizers; young plants may be damaged by termites; intolerant of waterlogged soils; a prohibited weed in Australia and a serious pest in many other countries.

Pongamia pinnata (L.) Pierre (Fabaceae; Papilionoideae)

Synonym: *Derris indica* (Lam.) Bennet. and 16 other names.

Origin and Distribution: Native to South and Southeast Asia; introduced to the Philippines, Australia, and subtropical U.S.

Ecology: In mesic tropics (0–1000 m, 500–2500 mm annual rainfall) on sandy and rocky soils.

Plant Characteristics: Deciduous, glabrous shrub or tree, 15–25 m high; aggressive, spreading roots; propagated by direct seeding, seedlings, cuttings, and root suckers; nitrogen fixing.

Main Uses: Fuelwood (calorific value of 4600 kcal kg^{-1}); fodder; oil (seeds); pest control (leaves); shade; medicine (leaves, flowers, bark, and sap); bark fiber for rope; apiculture; ornamental; soil improver; erosion control; press-cake is a pesticide, particularly against nematodes.

Comments: Tolerates saline soils; grows to full height in 5 years; spread through root suckers can become a weed; not a quality timber; host for the lac insect and for the hemiparasitic sandalwood, *Santalum album* (India); promising biofuel crop; dried leaves are stored with grain to repel storage pests; pounded and roasted seeds used as fish poison.

Populus deltoides Bartr. *ex* Marsh. (Poplar, Cottonwood)
(Salicaceae)

Origin and Distribution: Native to USA and Canada; introduced to Australia, China, India, Nepal, Netherlands, New Zealand, Pakistan, Sweden, United Kingdom.

Ecology: A wide range of habitats; prefers moist, well-drained, fine, sandy loams or silts, pH of 4.5–8; altitude up to 1000 m; mean annual temperature 8–14 °C; rainfall 600–1500 mm.

Plant Characteristics: Medium-sized to large tree, 20–30 m tall, 100 cm diameter at breast height; fast growth; propagation by cuttings; natural regeneration by seed; tolerates frost, heavy soil and waterlogging; intolerant to competition.

Main Uses: Timber (lumber, veneer, pulpwood and excelsior); fuelwood; fodder; tannin/dyestuff; medicine (bark, fresh flowers, leaves root); shade or shelter; soil improver; boundary planting; ornamental; windbreak; component of agroforestry.

Comments: Annual productivity 3 to 22 t ha^{-1}; widely used in the USA and Canada for amenity plantings; poplar-based agroforestry (poplar +wheat) popular in India (See Figures 12.5-12.7); hybrid poplars (e.g., *Populus deltoides* x *Populus nigra*; *Populus alba* × *Populus tremula*; *Populus deltoides x Populus trichocarpa*) exhibit very fast-growth rates; many clones available.

Prosopis cineraria (L.) Druce (The *Khejri* tree) (Fabaceae; Mimosoideae)

Synonyms: *Adenanthera aculeata* Roxb., *Mimosa cineraria* L., *P. spicata* Burm

Origin and Distribution: Native to India; introduced to West Asia and the Middle East.

Ecology: Occurs in dry lowland tropics (75–850 mm rainfall, 6–8 months dry period) on well-drained, light to heavy soils.

Plant Characteristics (See Figures 9.2, 9.16): Up to about 9 m tall with a spreading habit; thorny; N_2 fixing; deep-rooted; coppices; propagated by root suckers, seeds, and seedlings; light-demander.

Main Uses: Fuelwood and charcoal (2.9 m^3 ha^{-1} yr^{-1}); fodder; wood for posts, tool handles; green manure; afforestation; dried and green pods used as vegetable in many parts of the Thar desert in India; medicinal; gums/resins; tannins; soil improver; intercropping.

Comments: May become a weed in sub-humid environments; some populations display high genetic variability; tolerates saline soils, high alkalinity (pH 9.8), and seasonal waterlogging; suited for sand dune stabilization and reclamation.

Other major species of *Prosopis* in Agroforestry Systems (all adapted to dry regions; their taxonomy is not clear)

Prosopis chilensis (Molina) Stuntz: (The Mesquite Tree) Native to Argentina, Chile, Peru; introduced to Africa, Asia, and the USA.

Prosopis juliflora (Sw.) DC., syn. *Acacia juliflora*: Native to southwestern U.S., Central America; introduced to many arid zones of the world (e.g., Africa, and Asia).

Prosopis pallida (Humb. *et* Bonpl. *ex* Willd.) Kunth: dry parts of Peru, Colombia, and Ecuador.

Robinia pseudoacacia L.
(Fabaceae; Papilionoideae)

Synonyms: *R. pringlei* Rose

Origin and Distribution: Native to northeastern U.S.; introduced to European temperate and Mediterranean regions, as well as India, and Thailand.

Ecology: Grows in temperate and highland tropical regions (1500–2500 m, 300–1000 mm annual rainfall) on variable soils; does well on calcareous, well-drained loams.

Plant Characteristics: To 25 m; fast growth; deciduous; thorns on young branches; N_2 fixing; shallow root system; coppices; propagated by root suckers, direct seeding, seedlings, cuttings, and stump sprouts; drought-hardy (2–6 months); cold tolerant, does not tolerate waterlogging.

Main Uses: Fuelwood (sp. gr. 0.68, 4–10 m^3 ha^{-1} yr^{-1}); erosion control; nurse tree; timber; posts; fodder (high tannins in young leaves, and lectin proteins can interfere with livestock digestion); windbreak; ornamental; honey production; soil improver; mine-land reclamation.

Comments: Aggressive colonizer; tolerates slightly saline soils; grows well on poor sites as acidic as pH 4.8; pioneers on disturbed soils or burned sites; dominates early forest regeneration in many native forests; can be lopped annually.

Samanea saman (Jacq.) Merr. (The Rain Tree) (Fabaceae; Mimosoideae)

Synonyms: *Albizia saman* (Jacq.) F. Muell; *Pithecellobium saman* (Jacq.) Benth.

Origin and Distribution: Native to northern South America; now widely naturalized.

Ecology: Occurs in sub-humid to wet lowland tropics with less than 6-months dry season; a wide adaptability up to 1000 m altitude in both monsoonal and equatorial climates with an annual rainfall of 1000–2500 mm; tolerates seasonal dry periods (2–4 months).

Plant Characteristics (Figure 13.A.I.18)**:** To 40 m with a wide, spreading crown; fast growth; N_2 fixing; coppices; light-demander; propagated by direct seeding, seedlings, and cuttings.

Main Uses: Fuelwood (calorific value: 5200–5600 kcal kg^{-1}); food (pods); fodder (pods, leaves); timber; wood for crafts; shade (coffee, cacao); green manure; ornamental.

Comments: A valuable source of high-quality firewood and charcoal; but a strong market for woodcarvings makes the wood too valuable to be used as fuel; the tree, because of its large crown, is not good for croplands but is used in grazing lands.

Figure 13.A.I.18
Samanea saman: Animals seeking shelter from the hot sun under the tree. (Photo: ICRAF/World Agroforestry)

Senna siamea (Lamarck) Irwin et Barneby (Fabaceae; Caesalpinioideae)

Synonyms: *Cassia siamea* Lam., *C. sumatrana* Roxb., and several other names

Origin and Distribution: Native range is Asia; introduced to Africa, Americas and Oceania.

Ecology: Grows under a wide range of climatic conditions (humid through to arid), tolerates low (500 mm) and high rainfall (2800 mm); but cannot tolerate low temperatures (<10 °C); no exacting soil requirements; but prefers moist soils with good drainage; sensitive to poor drainage; soil pH 5.5–7.5.

Plant Characteristics: Medium-sized tree (10 to 12 m height); dense, round, evergreen crown; coppices; not an N_2 fixer; frost sensitive; endures dry period (4 to 6 months); fast growth.

Main Uses: Good quality durable timber; resistant to termites; often used for walking sticks, boxes, axe handles; erosion control; alley cropping (See Figures 6.5, 18.13); shelterbelts and windbreaks; afforestation in the dry zones of India; for reclamation of abandoned tin-mined areas in Nigeria; intercropping; shade tree for coffee, cocoa and tea, nurse crop for *Swietenia mahogani* to reduce borer attack, and a host for the hemi-parasite sandalwood; widely grown for fodder.

Comments: Invasive outside its native range; fodder for cattle, sheep, and goats but problems with alkaloids and other secondary plant compounds in the leaves, flowers and pods.

Sesbania grandiflora (L.) Pers.
(Fabaceae; Papilionoideae)

Synonyms: *Agati grandiflora* (L.) Desv., *Robinia grandiflora* L, and a few other names.

Origin and Distribution: Native to South and Southeast Asia; introduced to the Caribbean, Central and South America, Australia, and parts of Africa.

Ecology: Occurs in the moist lowland tropics (1000 mm annual rainfall, 0–800 m altitude); well-adapted to hot, humid environments; tolerates periodic flooding and a variety of soil conditions.

Plant Characteristics: Small, loosely branching tree, 8–15 m tall; fast growth; N_2 fixing; coppices but not vigorously; propagated by direct seeding, seedlings, and cuttings.

Main Uses: Fuelwood (sp. gr. 0.42, 4278 kcal kg^{-1}, 20–25 m^3 ha^{-1} yr^{-1}); fodder (pods, leaves); food (young leaves, pods, flowers); green manure; pulpwood; medicinal uses (leaves, bark); soil improver; living fence; live support for crops such as vanilla and pepper.

Comments: Complementary to many agricultural systems (Figure 13.A.I.19); harvested over short rotations (3 year); susceptible to beetle attacks; short-lived; does not tolerate repeated pruning.

Figure 13.A.I.19
Sesbania grandiflora on the bunds (risers) between plots of rice paddies in Java, Indonesia. (Photo: PKR Nair)

Sesbania sesban (L.) Merr.
(Fabaceae; Papilionoideae)

Synonyms: *Aeschynomene sesban* L. and 14 other names.

Origin and Distribution: Native to East Africa; widely introduced in tropical Africa and Asia.

Ecology: Native to subhumid tropics (300–1200 m, 350–1000 mm annual rainfall) on variable soils. In its native range, the plant grows along streams, swamp edges, moist and inundated bottomlands; tolerant to moisture stress and saline and alkaline soils.

Plant Characteristics (Figure 13.A.I.20)**:** Deciduous, short-lived perennial shrub or tree, 1–7 m tall; narrow-crowned; deep-rooted; single- or multi-stemmed; fast growing; N_2 fixing; coppices; propagated by direct seeding and seedlings; moderately shade tolerant.

Main Uses: Fuelwood and charcoal (calorific yield: 4350 kcal/kg); food (leaves and flowers); fodder (leaves and young branches); green manure; erosion control; windbreak for bananas, citrus, and coffee; soil improver; promising shrub for alley cropping and fallow improvement.

Comments: Open crown and slender habit permits understory crops; 30 t ha^{-1} yr^{-1} fuelwood yield; soft wood; rhizobium strains specific to host genotype required; invasive outside its native range.

Figure 13.A.I.20 *Sesbania sesban*, fast-growing green manure/fallow species for soil fertility improvement in the humid tropics. (Photo: ICRAF/World Agroforestry)

Syzygium aromaticum (L.) Merr. & Perr. (The Clove Tree)
(Myrtaceae)

Synonyms: *Eugenia aromatica* (L.) Baill., *E. caryophyllata* Thunb., *E. caryophyllus* (Spring)

Origin and Distribution: Native to Indonesia; exotic range includes Brazil, Haiti, India, Kenya, Madagascar, Malaysia, Mauritius, Mexico, Seychelles, Sri Lanka, Tanzania.

Ecology: Tropical evergreen tree; occurs in woodland and rainforests up to 1000 m elevation; 1500–2500 mm mean annual rainfall; prefers loamy humus-rich soils.

Plant Characteristics (Figure 8.16)**:** Small to medium sized, multi-stemmed tree, 8–30 m tall; seed propagated (require a pretreatment of soaking in water for three days); softwood grafting.

Main Uses: The unopened flower bud on the terminal shoots is the clove of commerce – an important spice; leaves, flowers and bark are aromatic; yields an essential oil; medicinal use.

Comments: Clove trees need light shade; interplanted with coconut palms; live for more than 100 years; Sumatra disease caused by *Pseudomonas solancearum,* a bacterium, causes die-back and mass decline.

Related Species:

Syzygium cuminii (L.) Skeels; **Synonyms:** *Eugenia cumini* (Linn.) Druce., *Syzygium jambolana* DC., and others. Native to India, Sri Lanka, and Myanmar; introduced into many other tropical and subtropical countries in Asia, Africa, Americas and Oceania.

Syzygium malaccense (L.) Merr. & L. M. Perry (Malay Apple): Southeast Asia and Polynesia.

Tamarindus indica L.
(Fabaceae; Caesalpinoideae)

Origin and Distribution: Native to semiarid tropical Africa; introduced to the Caribbean, Latin America, India, and Australia.

Ecology: Grows in lowland dry and monsoonal tropics (400–1500 mm annual rainfall) on well-drained, deep soils (pH 5.5); up to 2000 m altitude.

Plant Characteristics (Figure 13.A.I.21**):** To 30 m tall with a wide crown; evergreen; deep tap root; propagated by direct seeding (after hard seed coat is nicked), seedlings, or cuttings; coppices.

Main Uses: Food and seasoning (pod juice and pulp, leaves, and flowers); fodder (leaves and seeds); fuelwood and charcoal (sp. gr. 0.93; calorific value of 4850 kcal kg^{-1}); timber; firebreak; ornamental; shade; medicine (fruit, leaves, flower, bark); tannin (ash and bark); live fences.

Comments: Early growth is slow; fruits ripen well only in areas with extended dry seasons; production starts at 8–12 years and continues for up to 200 years; normally found associated with the Baobab tree (*Adansonia digitata*) in Africa; waterlogging not tolerated; tolerant of slightly saline soils; drought-tolerant; wood is easy to polish and termite-resistant; not an N_2 fixer.

Figure 13.A.I.21 *Tamarindus indica* – a popular tree on farmlands and countrysides throughout Africa and South- and Southeast Asia. (Photo: BM Kumar)

Terminalia amazonia (J.F.Gmel.) Exell
(Combretaceae)

Origin and Distribution: South America - Brazil, Bolivia, Peru, Ecuador, Colombia, Venezuela, the Guyanas; north through Central America to Mexico.

Ecology: Occurs in wet forests and swamps or open savannahs; mainly at lower elevations in the tropics from near sea level to below 1000 m.

Plant Characteristics: Moderately fast growing; evergreen tree with a large crown; up to 40 m tall; wide range of soils, including poor sands and clays, except the drier sites; seed propagated.

Main Uses: Shade tree (coffee, cacao); good quality wood; used for making high quality furniture, cabinets, flooring, ship building, tool handles, veneer etc.; bark a source of tannins.

Comments: Little studied; wood heavy, hard, and strong; elastic; moderately durable, resistant to dry woodborers, moderately resistant to fungi and termites.

Related Species

Terminalia brownii Fres. Tropical Africa: Nigeria and Cameroon to East Africa. Occurs in the dry to moist tropical areas, usually at elevations up to 600 m. Deciduous shrub or small tree up to 15 m tall. Used as fodder (leaves), fuelwood and charcoal; coppiced when young.

Terminalia ivorensis A. Chev. Western tropical Africa; large deciduous tree; 15 to 46 m tall; fast rate of growth; seed propagated; strong light demander and a good colonizer of abandoned farmlands; firewood and charcoal; shade (coffee, banana and cocoa) or shelter; intercropping.

Vitellaria paradoxa C.F.Gaertn (The Shea Butter Tree)
(Sapotaceae)

Synonyms: *Butyrospermum niloticum* Kotschy, *B. paradoxum* (C.F.Gaertn.) Hepper

Origin and Distribution: Indigenous to the Guinea and Sudan savanna zone from Senegal to Sudan, and to western Ethiopia and Uganda; characteristic tree of West African savanna.

Ecology: Occurs in open sites and parkland savannah; altitude 100–1200 m; mean annual temperature 24–32 °C; mean annual rainfall 600–1400 mm; prefers dry and sandy clay soils.

Plant Characteristics (see Figure 9.11): Small to medium-sized tree, 10–15 (max. 25) m tall; much branched, dense, spreading, round to hemispherical crown; light-demanding; seed propagated.

Main Uses: Flowers and fruits are important foods; shea butter extracted from the nuts is one of the widely used and inexpensive vegetable fats in Sahel (see Figure 22.8); apiculture; firewood (excellent quality); leaves, bark, and shea butter used in traditional medicines; soil improver, control soil erosion; suitable for intercropping; increasingly being used in cosmetics.

Comments: The shea tree, listed as "vulnerable" in the IUCN Red list, is one of the most important sources of vegetable oil in rural areas of the savanna zone of West Africa. Shea butter is a useful cocoa-butter substitute.

Ziziphus mauritiana Lamk (Ber or Desert Apple) (Rhamnaceae)

Synonyms: ***Ziziphus jujuba*** (L.) Lam., and several others.

Origin and Distribution: Native of South and Central Asia; now found in East and West Africa.

Ecology: Usually occurs in the semiarid tropics in regions receiving 250–500 mm annual rainfall at altitudes of 0–1500 m on light, sandy to medium, loamy, well-drained, moderately saline soils.

Plant Characteristics: Fast growing, thicket-forming shrub or tree; single or multi-stemmed; thorny; 2–12 m in height; deciduous during the dry season; deep rooted; propagated by seedlings, root suckers, and direct sowing; hardy tree; survives under extreme temperatures.

Main Uses: Edible fruits; live fences; fodder; sericulture; host for shellac insects; apiculture; fuelwood (sapwood has 4900 kcal kg^{-1}); good charcoal; poles and posts; wood for construction; sand-dune fixation; shade tree; ornamental; living fence (spiny stems deter livestock).

Comments: Commonly used for windbreaks; coppices; noxious weed in Australia; invasive in parts of southern Africa and on some Pacific and Indian Ocean islands.

Related Species

Ziziphus nummularia (Burm. f.) Wight et Arn; syn. *Rhamnus nummularia* Burm.f

Native to the Indian sub-continent (Figure 13.A.I.22). Found in the semiarid tropics and highland subhumid tropics. Thorny; multi-stemmed; to about 3 m in height; deciduous in dry season; propagated by seedlings and root suckers. Edible fruits; fodder; fuelwood.

Figure 13.A.I.22 *Zizyphus nummularia* with turmeric (*Curcuma longa*) as the understory crop in Rajasthan, India. (Photo: ICRAF/World Agroforestry)

Appendix II Shade-Tolerant Specialty Species

As noted in Section 13.4.1 (Shade-Tolerant Specialty Crops and Medicinal & Aromatic Plants), several so-called specialty crops are cultivated in agroforestry systems, especially in the tropics. They broadly fall under four categories: (1) **Commercial crops trailed onto woody perennial support trees** (perennial vines) – Prominent examples: black pepper (*Piper nigrum*) and vanilla (*Vanilla planifolia*); (2) **Perennial rhizomatous cash crops** that are grown under the shade of trees in natural stands and harvested like annuals – Prominent examples: cardamom (*Elettaria cardamomum*) and large cardamom (*Amomum subulatum*); (3) **Rhizomatous, botanically perennial species that are cultivated as annuals** under planted or natural stands of trees – Prominent examples: ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), ginseng (*Panax* spp.); and (4) **Medicinal and aromatic plants**, mostly annuals but also including some trees that are harvested annually and nondestructively like fruit trees – Prominent examples: Allspice (*Pimenta* spp.), clove (*Syzygium aromaticum*), and nutmeg (*Myristica fragrans*).

Out of the examples of ten species mentioned above, considerable commodity-centric information exists on some of the prominent ones such as black pepper and cardamom, whereas information on the commercially less-prominent and less widely cultivated ones such as ginseng and allspice is relatively limited. Brief descriptions of the ten species of the four categories identified are given below in the order in which the species are mentioned above.

Black pepper (*Piper nigrum,* Family: Piperaceae)

Black pepper, known as the king of spices, is one of the oldest spices of extraordinary importance in international trade. It is a native of the Western Ghats in peninsular India; is cultivated in India, Southeast Asia, and the New World Tropics. The plant is a perennial woody climber (Figure 13.A.II.1) growing up to 10 m height and is adapted to humid tropical climates with a well-distributed annual rainfall of 2,000 to 2,500 mm, on fertile well-drained soils; does not withstand prolonged flooding or drought. Pepper is cultivated in commercial plantations or as a component of the mixed species tropical homegardens and coffee and tea plantations. Being a climber, it needs to be trailed on to a support (called "standard") such as a wooden pole. The various MPTs in homegardens (Chapter 7) are used as support trees in smallholder production systems, whereas in commercial plantations, support trees are planted specifically for the purpose, the most common being *Erythrina* spp. and *Gliricidia sepium*. Fast growth, ease of propagation, light crown, tolerance to pests and diseases rough and non-exfoliating bark, and a deep root- system are the desirable attributes of a support tree for trailing pepper vines. The pepper vine is propagated by stem cuttings. Flowering and fruiting start in about three years after planting; fruits (spikes) ripen in four months after flowering, full production is attained in about five years and continues for up to 25 years. The plant is susceptible to several fungi and insects.

Figure 13.A.II.1 Black pepper around the trunks of trees, with cardamom leaves in the foreground, Kerala, India (Stock Photo)
(Various photos of pepper can be found in Chapters 7, 8, and Appendix I of this chapter)

Vanilla (*Vanilla planifolia*, Family: Orchidaceae)

Vanilla yields vanillin, the popular flavoring agent of commerce, from the fermented and processed beans (pods) of this orchid. Being the only member of the family Orchidaceae yielding a spice, it is called "orchid spice." The plant originated in Mexico and was introduced to many tropical countries in Asia and Africa, Madagascar being the major producer in the world today. The plant is a perennial succulent vine, and, like black pepper, it requires light overstory shade, a support for trailing (Figure 13.A.II.2) and humus-rich soil. Propagation is by stem cuttings; mulching is important. Plants flower in about four years. Natural pollination is impossible because the stamen and stigma are separated by a rostellum. In Mexico, some cross-pollination happens by bees, but commercially hand pollination is carried out; an individual worker handles 1000 to 2000 pollinations per day. Fruits mature in 7–9 months and should be harvested before they are fully ripe and are cured by alternate wetting and drying.

Figure 13.A.II.2 Vanilla trailing on the support tree (*Talipariti tiliaceum*) in Madagascar. (Photo: Dominik Schwab and Annemarie Wurz, Univ. of Goettingen, Germany) (Also see Figures 8.16, 8.17; Chapter 8)

Cardamom (*Elettaria cardamomum*, Family: Zingiberaceae)

Cardamom, known as the "queen of spices," is an important spice used for flavoring, chewing, and medicinal purposes, and is the second most important spice crop after black pepper. Sometimes it is referred to as *small cardamom* – to distinguish it from its larger variant, *Amomum* spp., known as *large cardamom* that is a taller plant and produces larger capsules. *E. cardamomum* produces the principal cardamom of commerce. The plant is indigenous to the mid-elevation moist evergreen forests of the Western Ghats in peninsular India; grows well on warm (10 to 35 °C) and humid (with >1500 mm of evenly distributed rainfall) mountain slopes (600–1500 m elevation), beneath a canopy of evergreen trees. Other major producers of the crop include Guatemala, Indonesia, and Tanzania. *E. cardamomum* is a perennial herb, 2 – 5 m tall; has a branched subterranean rhizome, from which arise 10 – 20 erect leafy shoots, and the panicles arise from the base of the shoots (Figure 13.A.II.3). The fruit is a trilocular capsule, pale green when mature; the seeds are about 3 mm long, dark brown, and aromatic. Cardamom is propagated by planting a section of the rhizome called the "bulb." The plant starts bearing in about 3 years and attains full bearing in 7–8 years after planting, and economic bearing lasts for about 15 years. The plant grows best under light shade provided by trees (Figure 13.A.II.4) thus, cardamom cultivation is a "typical" agroforestry practice.

Figure 13.A.II.3 Cardamom in full bloom: panicles originating from the leaf axils at the base of the plant in Guatemala. (Photo: PKR Nair)

Figure 13.A.II.4 Cardamom under shade trees in Kerala, India. (Photo: BM Kumar) – See also Figure 13.A.II.1

Large Cardamom (*Amomum subulatum, A. aromaticum*, Family: Zingiberaceae)

Large cardamom, also known as "black cardamom," is a native of the sub-Himalayan ranges, and India is its largest producer and exporter. Several species of the genus *Amomum* are distributed all over the mountainous areas from the Himalayas to southern China, Thailand, and Cambodia. Pods are used as a spice, much like the green Indian (small) cardamom pods but have a distinctly strong and smoky flavor and aroma. Just like small cardamom, large cardamom is a sciophyte (shade-loving crop) and it grows well under moderate to dense shade (25 – 70% light interception). Himalayan alder (*Alnus nepalensis*), a deciduous, nitrogen-fixing (actinorhizal) and fast-growing tree, is the most prominent shade tree; some fodder trees are also used for shade. The shade trees also serve as a fuelwood source for curing the cardamom, as well as yielding fodder and timber (See a photograph of *Amomum subulatum* given as Figure 8.15).

Ginger (*Zingiber officinale*, Family: Zingiberaceae)

The ginger plant, an important source of spice as well as herbal medicine, originated in the Indo-Malayan region but is now widely distributed in many countries around the globe. The dried rhizome constitutes the ginger of commerce. Ginger is slender perennial herb to 1 m tall; the rhizomes are thick and hard; is cultivated in the tropics under the partial shade of trees, from sea level to about 1500 m elevation and 1500 – 2500 mm annual rainfall, on soils that are deep, well-drained, and high in organic matter; does not withstand waterlogging. Is propagated by 3 – 5 cm long rhizomes (called setts); they germinate about two weeks after planting. The crop matures in about 9 months. Being a shade-tolerant plant, it is usually grown as an understory crop in the homegardens and tree plantations (Figure 13.A.II.5). Many traditional cultivars are important components of agroforestry, but only limited attempts have been made to evaluate the effects of varying shade levels on ginger productivity.

Figure 13.A.II.5 Ginger as the understory species in a three-year-old stand of *Ailanthus triphysa* trees in Kerala, India. (Photo: BM Kumar)

Turmeric (*Curcuma longa*, Family: Zingiberaceae)

Turmeric or "the golden spice of life", is a perennial herb (Figure 13.A.II.6) which originated in South and Southeast Asia, but is cultivated in the tropical and subtropical regions all over the world. Turmeric powder is extensively used as a food coloring and flavoring agent and it has many medicinal properties too, which can be attributed to a chemical constituent, curcumin (diferuloyl methane) – a non-steroidal, anti-inflammatory agent (3–4% by weight). Being a shade tolerant crop like ginger, turmeric is under-planted in several agroforestry systems in the tropics. Although many national research institutes have standardized the industrial turmeric production practices (e.g., Ravindran et al. 2007), aspects relating to shade requirement of the crop have not received adequate scientific attention, even though turmeric is a prominent understory crop in many traditional land-use systems.

Figure 13.A.II.6 Turmeric under oak trees in North Florida, USA. (Photo: PKR Nair) (Also see Figures 12.6 and 13.A.I.22)

Ginseng: *Panax ginseng* (Korean ginseng); *P. quinquefolium* (American ginseng), Family: Aralioideae

Ginseng is the root of plants of the genus ginseng, of which several species exist. It has been used in traditional medicines over centuries in Asian countries (mainly Korea and China) for its reported medicinal values. It is also cultivated in the eastern and central US and Canada and is found in rich, cool woods (Figure 13.A.II.7). In Korean cuisine, ginseng is used in various side dishes and soups), as well as tea and alcoholic beverages. Although commonly used as a dietary supplement, ginseng has not been approved by the US Food and Drug Administration (FDA) as a prescription drug. The shape of the root varies among species and has been used to distinguish types of ginseng. The root is most often available in dried form, either whole or sliced. Ginseng leaf, although not as highly prized, is sometimes also used. The Ginseng Growers Association of America, Inc. (GGAA: https://ginsengamerica.org) is a non-profit organization that was founded in the interest of growers and consumers of American ginseng represents ginseng growers in the United States, primarily in the state of Wisconsin. The short plant grows 3 to 7 compound leaves that drop in the fall and bears a cluster of red or yellowish colored fruits from June to July. It prefers a cool climate and grows well in the summer months under the trees and is commonly mentioned as an example of the Forest Farming practice of agroforestry in North America (see Chapter 10).

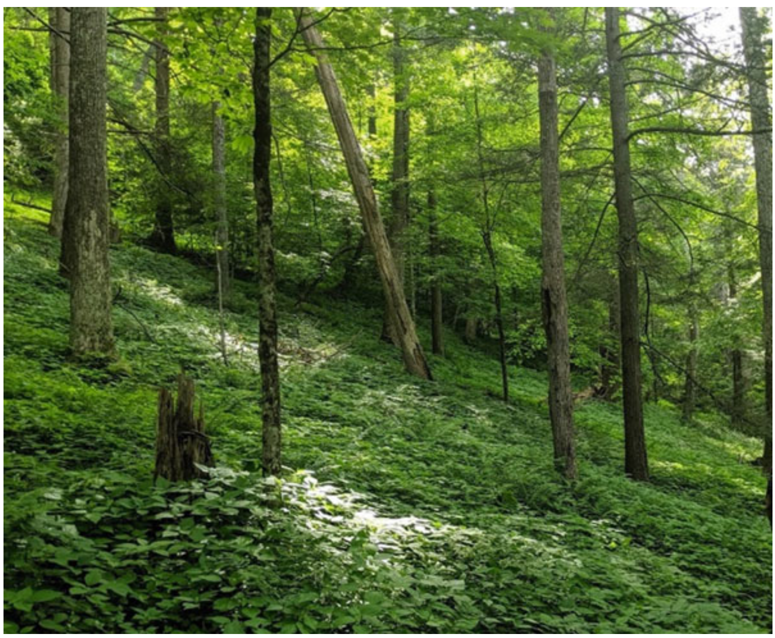

Figure 13.A.II.7
Ginseng under trees (Forest Farming) in Wisconsin, USA. (Photo: USDA/ National Agroforestry Center)
(Also see Figure 10.12, Chapter 10)

Allspice (*Pimenta dioica*, Family: Myrtaceae)

Allspice, known also as pimento or Jamaican pepper, is the dried, unripe berries of a small tree *Pimenta dioica*, and is a preferred culinary spice of commerce. It combines the flavors of cinnamon (*Cinnamomum zeylanicum*), clove (*Syzygium aromaticum*), and nutmeg (*Myristica fragans*), and hence the name. The plant, native to West Indies and Central America, is a small evergreen tree, up to 9 m in height, with a slender erect main trunk that is profusely branched in its upper part (Figure 13.A.II.8). In its natural habitat, it grows in hot humid (annual rainfall about 1500 mm) lowlands (up to 500 m altitude) in fertile well-drained soils. Propagation is by seed, or sometimes vegetatively by grafting or budding; starts flowering in 5 – 6 years, attaining full bearing in 10 – 15 years, and lasting for the subsequent few decades. Allspice is usually grown in agroforestry combinations in homegardens with bananas, maize, and other common crops, and in silvopastoral systems in commercial plantations.

Figure 13.A.II.8 Allspice tree in Jamaica (Stock photo)

Cinnamon (*Cinnamomum zeylanicum*)

Cinnamon bark (quills) is used as a condiment for flavoring cakes, confections, and curries. Cinnamon oil distilled from the bark and dried leaves is used in perfumes and in the synthesis of vanillin. The plant is a native of Sri Lanka and the Western Ghats of peninsular India. Now it is cultivated also in southeast Asia and Seychelles, but Ceylon (Sri Lanka) cinnamon is reputed to be of the best quality. It is an evergreen tree that grows up to 15 m tall if left undisturbed. When cultivated, the stems are repeatedly cut for extracting the bark, giving the plant a bushy appearance. The leaves are stiff and aromatic and reddish brown when young. The best cinnamon is grown at low altitude, but the plant grows up to 1800 m elevation from sea level. The plant is adapted to light overstory shade. It is propagated by seed. The stems are cut when they are about 2 m high and 2 – 5 cm in diameter, which is after about 2 years of growth. Harvesting is done during the rainy season, which facilitates easy peeling of the bark. The peeled bark is fermented in heaps, and when it contracts to a quill or pipe, is packed with multiple quills rolled together. Cinnamon is commonly grown in smallholder farming systems including homegardens and other agroforestry systems (Figure 13.A.II.9).

Figure 13.A.II.9 Three-year-old cinnamon (Stock photo)

Nutmeg (*Myristica fragrans*, Myristicaceae)
Two important spices are obtained from the fruits of this tree: nutmeg, the dried seed, and mace, the dried aril, and both are used for medicinal purposes and in sauces and ketchup. It is a native of the eastern island of Moluccas and is now cultivated mainly in Indonesia and other parts of southeast Asia and parts of India and the West Indies. It is a small tree, about 10 m tall, with thick and luxuriant foliage. Flowers are unisexual; the male and female flowers are produced on separate trees, and sex differentiation is difficult before the tree flowers. The fruit is a fleshy, pale yellow, smooth drupe. The plant prefers rich well-drained soil, partial shade, and a hot humid climate with no pronounced dry season. Normally propagated by seed, but vegetative propagation (inarching) is getting popular to overcome the difficulty posed by 6 – 8 years of delay in sex differentiation; attains full bearing in about 15 years after planting, and lasts for several decades. Nutmeg is usually grown in agroforestry combinations (Figure 13.A.II.10) in association with (under) larger trees.

Figure 13.A.II.10 Nutmeg tree interplanted under coconut palms in Kerala, India. (Photo: ICRAF/World Agroforestry)

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Plant-to-Plant (Tree–Crop) Interactions in Agroforestry Systems 14

Contents

Abstract

Plant component interactions refer to the effect of one plant (component) on another or the whole system. In agroforestry systems (AFS), since the woody perennials are dominant components, these interactions are usually referred to as tree–crop interactions or tree-animal interactions. Early assessments of the potential interaction effects in agroforestry were mostly deduced from existing information on agriculture, ecology, and forestry, and qualitative observations of traditional AFS. The topic received increasing scientific attention during the first two decades of AF research (the 1980s and 1990s), and the primary focus was on resource "capture" and sharing, especially the interception and use of radiation in tropical AFS. With the evolution of ecosystem services of AFS as a major area of research since the early 2000s, many interaction effects became recognized as ecosystem services. The major ecosystem services of AFS such as soil fertility maintenance, soil erosion control, regulation of the quantity and quality of soil water, carbon sequestration and climate change mitigation, biodiversity conservation, and others are discussed in the subsequent chapters of the book. The focus of this chapter is on the tree-crop interaction studies of the late 1990s. Interactions used to

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be described from different angles such as competitive, complementary, and supplementary; aboveground and belowground; in sequential and simultaneous systems; and so on. Some efforts were also directed toward the development of quantitative models. As in the case of many other aspects of agroforestry research, continuous and long-term measurement and monitoring of interaction effects are critically needed but have unfortunately not progressed satisfactorily.

14.1 Introduction

Component interaction in a system refers to the effect of one component of the system on the performance of the other components as well as the whole system. In agroforestry systems (AFS), the term refers to interactions between the woody (primarily tree) and the nonwoody (primarily crop) components. Since the woody perennials are the important components of all AFS, these interactions are usually referred to as tree–crop interactions. In AFS such as silvopastoral systems involving animals, the term could refer to tree–animal interactions; but, as mentioned in Chapter 9, the available research-based information on such interactions is rather rudimentary and much less than that for tree + crop systems. This chapter will focus on plant–to–plant (commonly called tree–crop) interactions.

14.2 Tree-Crop Interactions: Shifting Paradigms

The importance of interactions between the component species of AFS had been recognized right from the early stages of the development of scientific agroforestry. Indeed, these interactions, both ecological and economic, figured prominently in the early articulation of the concepts and definition of agroforestry (Chapter 2). Early assessments of the potential benefits of agroforestry including the interaction effects were mostly deduced from existing information on agriculture, ecology, and forestry (Huxley 1983; Nair 1993), and were mostly based on qualitative observations of traditional AFS (Nair 1989; Ong and Leakey 1999). The topic received increasing scientific attention during the first two decades of organized agroforestry research (in the 1980s and 1990s) when several reports on the quantitative and analytical bases of interactions became available from a range of climatic and geographic regions in the tropics (Sanchez 1995; Huxley and Ong 1996; Rao et al. 1998; Ong et al. 2014). The focus of these efforts was on the interception and use of radiation, or resource "capture" in AFS (Ong and Black 1994). Gradually, the complexity and the nature and extent of interactions in AFS vs. annual intercropping systems became quite evident. Of considerable importance is the realization that the components in AF systems are "unequal", the trees being dominant and perennial. Moreover, interactions in AFS are continuous, rather than seasonal as in annual-crop systems, and the course and extent of interactions are largely determined by the tree component of the system (Rao et al. 1998).

Such interaction studies have been limited to tropical AFS. This is understandable given the differences between the tropical and temperate AFS in terms of the perceived role of agroforestry *per se* in the local land-use and of the trees in such systems. In the low-input, resource-poor land-management systems and inherently poor soils of the tropics, agroforestry was promoted as a land-management option to offset some of these constraints to agricultural production and livelihood security. The underlying scientific rationale was that the attributes of some trees that provide food, fodder, and fertilizer, and simultaneously support crop production through a variety of their soil- and climate-ameliorating functions could be effectively exploited. In the temperate regions, on the other hand, the primary role of trees in agroforestry is to facilitate and support crop production through environmental services to help conserve soil and reduce soil erosion, besides providing other ecosystem benefits. The ecosystem services embodying a broader operational set of attributes that integrate the beneficial effects of the tree–crop interactions and other tree-mediated advantages such as soil conservation became a major role and expectation from AFS in the temperate regions.

Thus, the tree–crop interaction has a tropical connotation, whereas the term ecosystem service has a larger global "appeal." With the evolution of ecosystem services of AFS as a major area of research since the early 2000s, many of the interaction effects became recognized and got integrated as part of the studies on ecosystem services. The major ecosystem services of AFS such as soil fertility maintenance, soil erosion control, regulation of the quantity and quality of soil water, carbon sequestration and climate change mitigation, biodiversity conservation, and others are discussed in the later sections of the book (Chapters 16, 17, 18, 19, 20, 21, 22, and 23). This chapter will review the major results of the plot- and field-scale measurements and evaluation of the direct, local effects of the tree–crop interactions that were undertaken primarily in the tropics during the 1980s and 1990s.

14.3 The Complexity of Tree–Crop Interactions

14.3.1 Different Ways of Looking at Interactions

Historically, different groups of scientists have described the interactions differently according to their disciplinary perspectives. In the ecological literature, the types of interactions in two-species populations have been described based on the net effect of interactions, by such terms as *commensalistic* (positive, "+", effect on species one and no observable effect, "0", on species two); *amensalistic* (-, 0); *monopolistic; predatory* or *parasitic* (+, -); and *inhibitory* (-, -) (Trenbath 1976; Pianka 1988). To these, *synergistic* or *mutualistic* (+, +) could be added as an interaction where the net effects are positive for both species. These concepts of observable net effects can also be expressed by terms such as complementary, supplementary, and competitive, as depicted in Figure 14.1; they are used to describe economic interactions as well.

Competition between species in mixed stands (interspecific competition) differs from that in monocultures (intraspecific competition) as the component species of agroforestry systems may impose differing demands on available natural resources (Black et al. 2014). Competition is greatest when species requirements are similar, to the point where those with overlapping niches cannot coexist in the same community. Therefore, as Vandermeer (1989) suggested, competition is greater between similar species as in monocultures where the species are of the same genotype than those with contrasting growth habits and genetic make-up. In such monoculture situations, complementarity between species is restricted because they compete for finite supplies of light, water, and nutrients. Although intraspecific competition is intense, the maximum attainable biomass for individual crops is strongly influenced by light, water, and nutrient supplies; to increase productivity, crops must capture more of these resources and/or use them more efficiently. In AFS, the component species differ greatly, and the growth of understory species may be inhibited by shade (see Chapter 12) and competition for water and nutrients. Other conditions being equal, competition for light is mostly the primary limitation, although water and nutrients are also often major limiting factors.

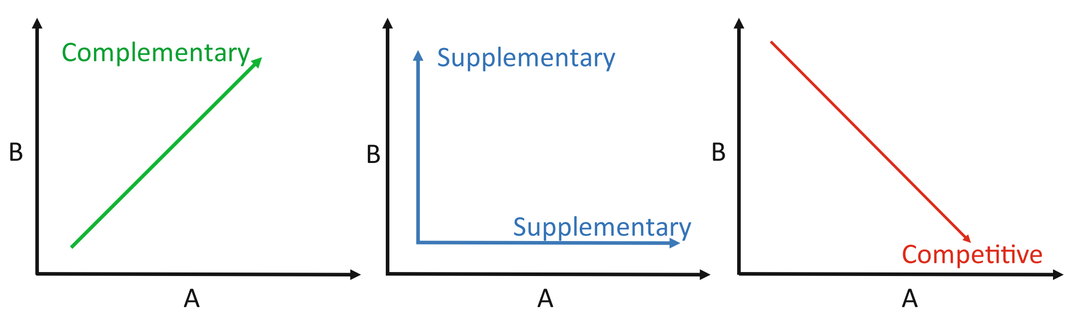

Figure 14.1 Types of simple interactions in a two-component system. Source: The first edition of the book (Nair 1993)

As opposed to competition, complementarity in resource sharing is a major feature and opportunity in AFS, where dissimilar growth habits and resource needs between the tree and crop components allow harmonious association between them. Indeed, the various AFS, especially the homegardens (Chapter 7) and shaded perennial systems (Chapter 8), clearly illustrate the success of complementary sharing of resources among the different components. Various attributes and growth habits of different components of AFS such as reduced light saturation levels and shade adaptability of understory species, distinct root-system patterns (as in multistory cropping – see Figure 8.23), growth- and canopy characteristics (such as coppicing ability and sparse canopy) of some overstory species and their adaptability to harsher environments (soil and water conditions), and many other such features add to the complementarity of several agroforestry species.

The terms “belowground” and “aboveground” are commonly used as adjectives to describe interactions (mostly competitive) between components for growth factors absorbed through roots (nutrients and water), and those absorbed/intercepted through leaves (mainly radiant energy), respectively (Singh et al. 1989; Monteith et al. 1991; Ong et al. 1991). While a large body of literature exists on aboveground interactions, information on belowground interactions is relatively limited. This is primarily because of the challenges associated with analyzing belowground processes and resource use by plants, especially the methodological difficulties in characterizing tree root systems (Malezieux et al. 2009; Faget et al. 2013). Belowground competition is also known as *root competition*, which arises largely because of the overlapping root systems, an observation that had been almost a century ago (Clements et al. 1929). While some researchers have reported that the tree component in a tree+grass system may suppress nutrient uptake by the grass component (George et al. 1996), others (van Noordwijk and Purnomosidhi 1995) have suggested that root competition may mask the numerous advantages that woody perennials may confer for the sustainability of agroforestry systems.

Partitioning the interactions into aboveground and belowground groups provides a sound basis for studying the processes involved as well as suggesting improved management options for components and systems. The net effects of interactions cannot, however, be easily be separated strictly into aboveground and belowground effects so long as the yield (or output) from the system which is a combined expression of belowground and aboveground processes, is taken as the measure of the total effect of interaction. Therefore, sometimes these interactions are grouped based on their net results as positive (beneficial) and negative (harmful).

In the interaction studies in tropical AFS during the 1990s, the AF systems used to be broadly categorized into two groups and the interactions used to be represented differently for the two groups: 1) simultaneous systems, in which trees and crops are grown together in different spatial arrangements; examples include trees on croplands, hedgerow intercropping (HI), intercropping in perennial-tree–crop stands, and multistrata systems; and, 2) sequential systems, in which trees and crops are grown in rotation; examples include rotational bush fallow or planted tree fallows followed by crops (Sanchez 1995). Some systems, such as *taungya*, rotational HI, and relay-planted tree-fallows combine the features of both simultaneous and sequential systems. Separate equations and protocols were proposed to study the interactions in these two types of systems (see Rao et al. 1998). However, a distinction between simultaneous and sequential systems could be confusing on small farms where spatial and temporal interactions and boundary effects are far more intense per unit area of land than in larger farms. Furthermore, many of the interactions are interdependent, for example, the nexus between soil chemical, physical and biological changes, and organic inputs. Therefore, interaction effects for these variables cannot be experimentally estimated independently.

14.3.2 Root Plasticity and Belowground Interactions

Root (phenotypic) plasticity refers to the ability of tree roots to respond to changes in the local (belowground) environment caused by factors such as nutrient availability and impervious soil layers. Roots generally proliferate in nutrient-rich soils and evade nutrient-poor loci. Many plant species show such "plastic" responses in their vertical as well as lateral root distribution patterns (e.g., Lehmann et al. 1998) to avoid competitive interactions (Ong et al. 1996; Schroth 1998; Zamora et al. 2007). Reviewing the literature on the topic, Callaway et al. (2003) emphasized that phenotypic expression of neighborhood effects on root systems occur either through direct effects of soil resources (abiotic environment), or independent of soil resources (i.e., neighbors, and herbivory) resulting in an alteration of competition in integrated tree+crop production systems.

Overall, studies on root interactions in agroforestry are rare. In one of the studies of this nature, Wu et al. (2016) reported that while rubber trees (*Hevea braziliensis*) in sole stands relied heavily on shallow soil water (< 30 cm), rubber trees in a rubber + *Flemingia macrophylla* agroforestry systems greatly expanded their water absorption zone to deeper soil layers improving the water use efficiency of the rubber trees. From a 3-year study on the effects of the tree–root competition and fertilizer application (poultry litter vs. inorganic) on soil nutrient status with time in a pecan (*Carya illinoensis*)+cotton (*Gossypium hirsutum*) alley cropping system on an Ultisol in northwest Florida, USA (see Chapter 10, Figure 10.3), Allen et al. (2006) reported that the competition for phosphorus (P) between the tree and the crop roots was minimal. In terms of potential environmental risks from P accumulation and loss via runoff or leaching in these soils, the organic fertilizer appeared to pose a greater long-term risk than the inorganic fertilizer if the application rates were based on the plant's nitrogen (N) requirement (which is the common practice) rather than P requirement. Kumar and Jose (2018), reviewing the literature on root systems of mixed-tree systems, suggested that two or more tree species growing close together may cause diminished lateral spread and/or deeper root penetration and that the closer the tree components the greater will be the subsoil root activity. They proposed that phenotypic plasticity could make the tree roots grow deeper in the soil, and create a "safety net" of distinct advantage to the trees to absorb nutrients that had leached down to the deeper soil without being intercepted and taken up by the shallow-rooted crops (see Chapter 16, Section 16.5.3) for more information on the safety net concept). It is not clear, however, to what extent the results from tree+tree systems could apply to tree+crop systems.

14.3.3 Multiple Factors and Processes of Interactions

The study of interactions in agroforestry requires the examination of several complex processes, listed in Table 14.1 (Rao et al. 1998). All the listed factors have, however, not been studied equally or adequately. The major factors studied relate to soil fertility (including soil's chemical, physical, and biological interactions), soil conservation, competition (between trees and crops for soil water, soil nutrients, and radiation), and microclimate (Akyeampong et al. 1995). According to Ong et al. (2014), there is no quantitative experimental evidence concerning the effectiveness of agroforestry in controlling weeds and allelopathy, although there are theoretical reasons to expect such benefits. Ample evidence is available, however, that overall biomass production in AFS is generally greater than in annual cropping systems – and higher biomass production is mostly considered as the indicator of positive interaction. The extent to which the positive interactions of each of these major factors are utilized for better management of the system is discussed separately in different chapters dealing with the individual ecosystem services (Chapters 16, 17, 18, 19, 20, 21, 22, and 23).

Quantifying the magnitude of interactions involving all these factors over a range of species, soil, management, and climatic conditions – although complex – will help determine the biophysical limits of the system. Efforts in that area have not made significant progress despite the promising beginning in the early 1990s and the development of some quantitative equations (Ong 1995; Rao et al. 1998). As the informative review

Table 14.1 Major tree-crop-soil interactions in tropical agroforestry

Nature of interaction	Process
Soil Fertility: Chemical	
• Carbon	Increase in active pools of soil org. matter
• Nitrogen	Increased soil N supply through
	• Biological N2 fixation
	• Deep capture of soil N
	• Reduced leaching
• Phosphorus	Transformation of less available to available inorganic P
• Cations (Ca, Mg, K)	Relocation in soil
Soil Fertility: Physical	• Increased soil aggregation and porosity
	• Reduced soil bulk density
	• Break up of hard pans/compacted layers
Soil Fertility: Biological	• Build-up of soil microbial populations
	• Build-up of Rhizobial and VAM populations
Microclimate	Shading: reduced soil and air temperature
	Protection: from heat and wind
Resource conservation	Reduced soil erosion and leaching
Weeds, pests, and pathogens	Alterations in populations
Allelopathy	Release of allelochemicals that inhibit growth of some plants

Source: Adapted from Rao et al. (1998).

by Ong and Kho (2014) shows, these efforts have remained conceptual at best, without adequate experimental validation under field settings. The focus of these interaction studies was mostly on biophysical factors and the study procedures were developed accordingly, but the enthusiasm in pursuing such lines of research has waned over the years. Some efforts that were made to extend such concepts to the socioeconomic arena did not gather much momentum either.

14.4 Measurement of Tree–Crop Interactions

14.4.1 Crop Yields as Indicators

Since quantitative procedures for measuring the individual effects of the interacting factors have not been developed, the overall yield of the annual crop is taken as the net effect of all interaction effects. This procedure has been followed in assessing the interaction effects in tropical alley cropping, which is the main – if not the only – practice on which much of the tree – crop interaction research has focused. Two sets of results from such studies are presented here as examples.

Tropical alley cropping: Some of the results of short-term alley cropping trials conducted on diverse soils in different parts of the tropics, especially sub-Saharan Africa, have been presented in Chapter 6. Notable among them is a comprehensive analysis conducted by Rao et al. (1998) on the performance of 29 alley cropping studies over a wide range of soil and climatic conditions in the tropics (Figure 6.2), and further presentation of those results in a generalized form (Figure 6.8) by García-Barrios (2003). Those results showed that annual crop response to interaction with hedgerow species can change strongly along productivity gradients and according to crop species. However, generalizations of interaction effects based on yield responses that are inherently location-specific and management-sensitive can be difficult and misleading.

Competition for growth resources: The relative importance of various hedge/crop interactions to crop yields in humid tropics was illustrated by Rao et al. (1998) using the results of a long-term experiment at Lampung, Indonesia (average annual rainfall 2200 mm) for three contrasting tree species – gliricidia (*Gliricidia sepium*), leucaena (*Leucaena leucocephala*), and peltophorum (*Peltophorum dasyrrachis*). The interaction effects considered were: (1) soil fertility, which was partitioned into the cumulative long-term effect of soil chemical, physical and biological changes (determined by removing hedgerows eight years after their establishment) and short-term effect primarily due to the current addition of mulch (determined by transferring to sole maize an equivalent amount of mulch produced by hedgerows in HI), and (2) competition, which was partitioned into competition for light (or shade effect) and belowground resources (determined with/without root barriers). The effects due to mulch and root interactions were small for all three species (Figure 14.2). Both the fast-growing leucaena and the open-canopy gliricidia provided large positive fertility effects and negative shade effects. Peltophorum – a slow-growing, non-N_2-fixing species, with a compact canopy – also exhibited a substantial positive fertility effect, but contrary to the other species, showed only a small negative effect due to shade. The combined result of the different interactions on intercropped maize yield was negative with leucaena and gliricidia possibly because the positive fertility effect was offset by the negative shade effect; only peltophorum, which showed the lowest shade effect, resulted in a net positive effect on maize (ICRAF 1995). The study questioned fast growth and N_2 fixation as criteria for selection of species for HI, and suggested that species that supply high N per unit shade (such as peltophorum) would be appropriate for the humid tropics (van Noordwijk et al. 1995). The shade of hedgerows may have no effect on shade-tolerant, short-duration crops, while it may generally have a negative effect on other short-statured shade-intolerant crops. Results of some other studies during the 1980s and 1990s on competition between hedgerows and crops for water and nutrients in tropical alley cropping that used to be presented as effects of competition on crop yields are now supplemented with additional information and reported under "other ecosystem services" (Chapter 22) related to hydrological factors (water competition and availability, and water quality enhancement) and plant health (pests and diseases).

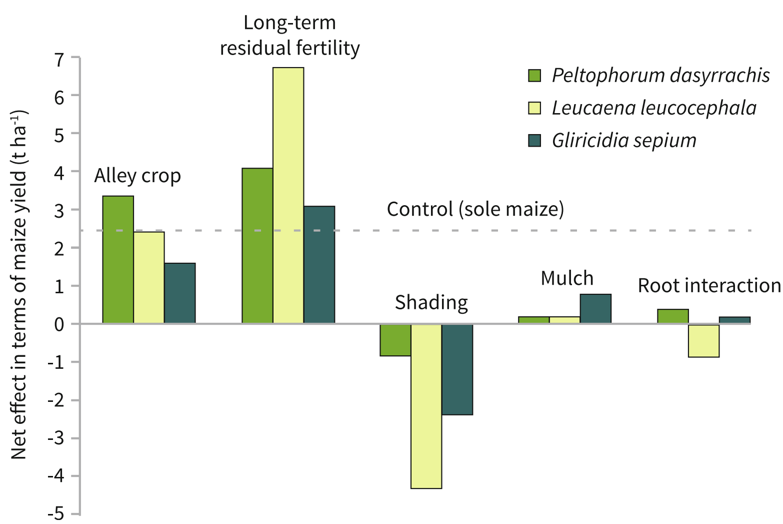

Figure 14.2 Net effects, expressed in increase or decrease of maize grain yield, of long-term residual soil fertility (estimated by removing hedgerows), short-term mulch (estimated in terms of response of sole maize to equivalent amount of prunings produced by hedgerows), root interactions (estimated from yields with and without root pruning) and shading (estimated by difference) in an eight-year-old hedgerow intercropping system with three contrasting tree species in North Lampung, Indonesia. The results are based on yields from the 1994 first rainy season, with the above treatments applied eight years after the establishment of the trial. The alleycrop yield is assumed to reflect the net result of various hedge–crop interaction effects. (Source: ICRAF 1995)

14.4.2 Land Equivalent Ratio

Land Equivalent (or, *Equivalency*) Ratio (*LER*) is a commonly used index for evaluating the effectiveness of mixed cropping and assessing the relative performance of a component of a crop combination compared to sole stands of that species (Willey 1979; Vandermeer 1989; Nair 1993). It is the ratio of the area under sole cropping to the area under intercropping, at the same management level, that is required to provide an equivalent yield, and is the sum of the fractions of yields of the intercrops relative to their sole-crop system yields:

$$LER = \frac{X_i}{X_s} + \frac{Y_i}{Y_s}$$

where X and Y are the yields of the component crops in either an intercrop (i) or a sole crop (s)

To present it slightly differently, LER is the sum of relative yields of the component species:

$$LER = \sum_{i=1}^{m} \frac{yi}{yii}$$

yi = yield of the i^{th} component from a unit area of the intercrop,
yii = the yield of the same component grown as a sole crop over the same area, and
the ratio *(yi/yii)* is the relative yield of component i.

To compute LER, the relative yields of all components of the mixture may be summed. When LER is unity (= 1), there is no additional production advantage of mixed culture; when LER is less than unity, there is a disadvantage, and when LER is more than unity, there is an advantage. When LER is measured at a uniform overall density of the species, grown both as an intercrop and a sole crop, LER will be equal to the relative yield total (RYT). However, in most agroforestry systems, the plant density of component species will not be the same as in a sole crop stand of the same species, and LER values may vary with different density levels. The definition of LER requires that the sole crops used in calculations be at their optimum densities, but few LER measurements have been made using sole crop data from a range of densities. If the performance of an intercrop at some arbitrary density is to be compared with that of a sole crop at its optimum, it would be necessary to use the intercrop's performance measured at its optimum density. Normally, constant density LER (RYT) is used when the objective is to identify beneficial crop combinations. Another drawback of LER in comparing agroforestry with monocropping is the unequal duration of land occupancy by the two systems. The tree component of AFS will occupy the land throughout the year whereas the crop (agricultural) component's land occupancy is seasonal. To overcome such difficulties, some improvements such as Area-Time-Equivalency-Ratio (ATER) have been proposed (Hiebsch and McCollum 1987), which is an adaptation of LER that takes account of land left unused after harvesting the shorter duration crop component. Some field measurements of LER and ATER have been reported in agroforestry literature (Jama et al. 1995; Bellow et al. 2008). Such evaluation methods, however, have not been widely adopted in agroforestry.

14.4.3 Tree-Crop Interaction Models

Models represent an idealized, simplified representation of reality and are increasingly being used to get insight and direction to understand and manage agroecosystems (e.g., the WaNuLCAS model: see Chapter 20, Section 20.4.2; Table 20.4). It is also widely acknowledged that the models are only as good as the assumptions upon which they are based. Reviewing the developments in the tree–crop interaction studies in agroforestry, Ong et al. (2014) recognized three approaches to tree-crop interaction models: (1) separating positive and negative effects; (2) the resource balance approach, and; (3) modeling resource capture. The goal of all three approaches is the same: to understand and predict yield performance over a wide range of biophysical situations. However, other than describing the generalities of the various approaches, no clear results have been reported, making the authors succinctly allude to the well-known dictum that "***All models are questionable, but some may be useful***" (Box and Draper 1987).

14.5 Management of Tree–Crop Interactions

The magnitude of interactive effects between trees and other components of agroforestry systems depends on the characteristics of the species, their planting density, and spatial arrangement and management of the trees. Manipulating the densities and arrangements is probably the most powerful method for capitalizing on the beneficial effects of trees while reducing the negative ones. However, in some cases, for example, when trees are used as supports for crop plants, the planting density of the trees is determined by the planting density of the crops (e.g., black pepper, *Piper nigrum*, production system involving support trees; Figures 8.19, 8.20, and 8.21). Therefore, in these cases, choosing a wider plant spacing for trees with larger crowns may not be a valid option; under such conditions, knowledge of the light transmission characteristics of the tree crowns and the options for tree management will become important.

A common strategy to offset competition for water between the tree and crop components especially under water-scarce situations is the use of root barrier treatments such as trenching or installation of plastic/metallic sheets in the rhizospheric region. Such treatments are management options to spatially isolate tree/shrub roots from crop roots and help reduce interspecific competition for belowground resources, but, of course, not to exploit any positive interaction. Other options to reduce evapotranspiration and the trees' demand for water include reduction of tree densities (either through controlling initial population density or through subsequent thinning interventions), adopting tree management practices (see the next paragraph) and making use of tree prunings as mulch (discussed in Chapter 6). Although the canopy reduction treatments have been claimed to reduce the lateral spread of roots, the claim has not been supported by field data. Planting crops, palms such as coconut (*Cocos nucifera*) and areca (*Areca catechu*), and a whole host of other species on raised beds in low-lying and waterlogged soils as in salt-affected lands (see Chapter 18, Section 18.7.3) are common management practices developed for areas with specific land management problems. Such practices do not necessarily involve the exploitation of the tree–crop interaction in the agroforestry context as discussed in this chapter.

***Shade regulation of overstory species*:** Several characteristics could be identified as desirable attributes for trees in agroforestry systems; but often it is not possible to choose trees with all these characteristics, either because other plants are already established, or because production or protection goals favor the choice of other species (see the discussion on tree ideotype in Chapter 13, Section 13.5.2). Whenever a tree species with all the desired characteristics is not available (which is likely to be the case in most situations), tree crowns and roots can be manipulated through management operations, mainly by pruning and thinning. Figure 14.3 illustrates the tree management and shade-regulation operations that are commonly done in forestry and horticulture. Other common management operations such as fertilization, application of mulch and manure, cut-and-carry fodder systems, and confinement or rotation of the animals can also be employed. The different manipulations can be grouped as growth-enhancing or growth-reducing according to their effect on the targeted component.

The goals of management practices should be to increase the production of the desired products and to decrease growth and, hence, the competition of undesired components. In many cases, one cultural treatment will accomplish both goals simultaneously, e.g., in the case of pruning trees in tropical alley cropping and applying the biomass to the soil. While the removal of parts or all of the crown will reduce the tree's competitive ability, it will help increase the growth of the associated intercrop by providing green manure and by allowing more light to penetrate to the

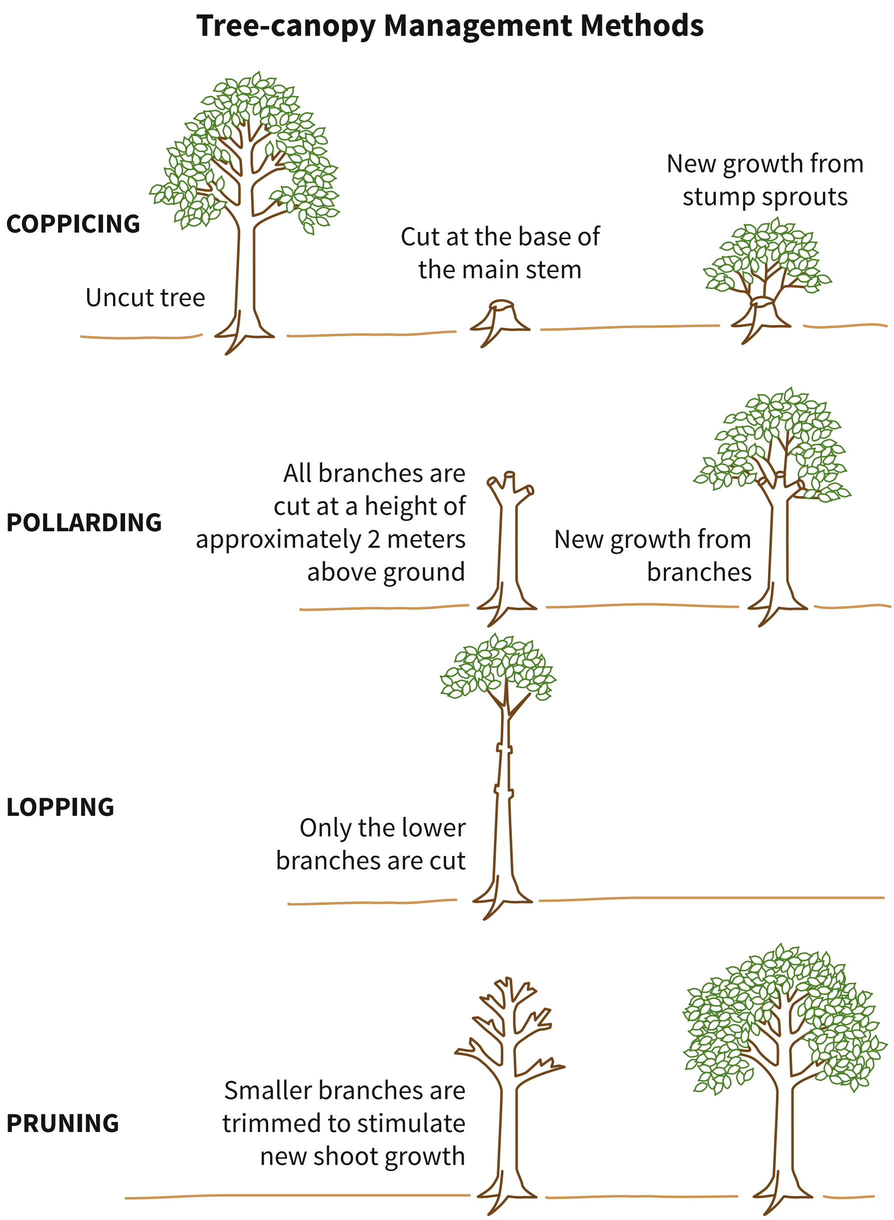

Figure 14.3 Tree-canopy management methods

crop. Belowground competition may also be reduced as a result of pruning-induced root die-back (Cannell et al. 1996; Cannell 1990). These observations also apply to the pruning or pollarding operations on trees grown for shade or as live supports, such as legumes of the genera *Erythrina*, *Inga*, or *Gliricidia*. Species such as *Erythrina berteroana*, which have large thick leaves and high rates of biomass production when grown as a shade tree, will require more intensive pruning than trees with a less dense canopy such as *Gliricidia sepium* (Nair and Muschler 1993). Under conditions of severe belowground competition, root pruning operations or trenching may eliminate, or strongly reduce, the negative effects of the trees on the intercrop, as mentioned earlier. In an alley cropping system with *Leucaena leucocephala* in a semiarid area of India, Singh et al. (1989) demonstrated that the construction of a root barrier eliminated any yield reduction of cowpea (*Vigna unguiculata*) and sorghum (*Sorghum bicolor*) grown in the 10 m-wide alleys. Similar results were obtained in an alley cropping system with *Senna* (syn. *Cassia*) *siamea* and *Leucaena leucocephala* in Togo, where the roots were cut biweekly to plowing depth; the growth of maize (*Zea mays*) plants close to the hedgerows was less reduced than in treatments without root cutting (Schroth 1998). However, these operations tend to be extremely labor- and cost-intensive and therefore may only be acceptable in unique settings.

14.6 Concluding Remarks

Interspecific interactions between plants have been studied rigorously in plant ecology and crop physiology and the results applied in the design of intercropping systems of annual crop mixtures. Recognizing the relevance of such interactions in tree + crop combinations, it became a prominent research topic during the early stages of tropical agroforestry development in the 1980s and 1990s with the emphasis on extrapolating from existing information in allied disciplines. Gradually, a substantial body of literature of quantitative and analytical bases of interactions became available, primarily on shade effects and interception and use of radiation from a range of climatic and geographic regions in the tropics. However, the lack of clearly defined parameters as indicators of interactions and procedures for their quantitative measurements added to the difficulties in pursuing such research. With increasing interest in the broader and application-oriented concept of ecosystem services and the dominance of climate change as the major ecosystem-related environmental issue since the early 2000s, research interest in interspecific interactions *per se* waned gradually. Nevertheless, being a topic of considerable importance in mixed-species agroforestry systems of annuals and perennials, research interest in the topic might resurface.

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Section IV

Biophysical Foundations of Agroforestry: Soil Productivity and Protection

Soils and Agroforestry: General Principles

15

Contents

Abstract

Proper management of soils has been central to the welfare of human society since very early times. An understanding of the nature and properties of soils is, indeed, critical to the success of any land-use system. Since the beginning of agricultural research in the mid-1800s, soils and soil-related aspects including plant nutrition were dominant themes in land-use R & D (research and development) portfolios all over the world. Thanks to these efforts, soil science has developed into a well-researched and prominent discipline endowed with a rich and voluminous literature base. This chapter presents a general introduction and briefly reviews the common terms used in soil science that are essential for understanding the major soil processes and ecosystem services. The topics and terms explained include those related to soil formation; physical, chemical, and biological properties of soils; soil types and classification; soil-derived

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plant nutrients; soil management, and a brief note on some special characteristics of tropical soils. The major terms used in the chapter are also included in the Glossary of the book.

15.1 Introduction

Soil is one of the most important natural resources that supports all forms of terrestrial land use, and its proper management has been central to the welfare of human society since very early times. Food shortages caused by soil mismanagement and environmental destruction have undermined several ancient civilizations. The collapse of the Sumerian civilization in the Near East and the Mayan Empire of Mexico are two such classical examples narrated by Nair and Toth (2016). During the Sumerian civilization (that occupied a region in the lower valley of the Euphrates River, fifth to third millennium BC), a flaw in the irrigation practices led to rising water tables causing high soil salinity levels and serious crop failures. Once that tipping point was reached, starvation quickly destabilized and ultimately led to the demise of Sumerian society (Ponting 2007). As the Mayan Empire (Mexico, 2000 BC to 600 AD) continued to seek arable land and fuelwood, it encouraged deforestation leading to severe declines in soil productivity and high levels of soil erosion especially in the mountainous terrain of what is now Guatemala. The loss of productive capacity of the soils soon led to human malnutrition, leaving the weak society to warfare over limited resources and eventually the collapse of the Empire (Turner and Sabloff 2012). Based on such historical examples, as well as numerous experiences in the modern era, it became well recognized that an understanding of the nature and properties of soils is the key to the successful management of all land-use systems. Franklin D. Roosevelt, the 32nd President (1933–1945) of the United States who directed the federal government during most of the Great Depression (1929–1939), famously said: "A nation that destroys its soil, destroys itself."

An understanding of the nature and properties of soils is, indeed, critical for understanding the principles of agroforestry and the success of the practice. The objective of this section of the book is to explain these principles of soil management for agroforestry and the potential benefits that could be derived by adopting science-based practices that are based on such principles. This chapter will present a general introduction including brief explanations of common terms used in soil science and elements of soil classification. The subsequent chapters will deal with major soil processes such as soil fertility improvement, organic matter dynamics, and nutrient cycling (Chapter 16), nitrogen fixation (Chapter 17), and soil conservation (Chapter 18). Ecosystem services, such as climate change mitigation through soil carbon sequestration, that are also intimately related to soil properties and management will be considered in the next section (Part V).

15.2 Soils and Agroforestry

One of the most widely acclaimed advantages of agroforestry is its perceived potential for conserving the soil and maintaining its fertility and productivity. Presumably, it was based on this premise that agroforestry came to be identified initially as a land-use activity in and for the tropics where the soils, in general, are inherently poorer and less productive than those in the temperate zones (this perception about the tropical focus of agroforestry, however, has changed since then: see Chapter 10). Consequently, and possibly because of the soil-science background and interest of several of the early researchers in agroforestry, soil productivity became one of the first areas of thrust in scientific agroforestry. The first international consultative scientific meeting organized by ICRAF was on soil research (Mongi and Huxley 1979), and a few other comprehensive reviews on this topic by ICRAF scientists were published during the 1980s (Nair 1984; Young 1989). This early momentum on soil-related investigations and initiatives has continued ever since in agroforestry R & D (research and development).

The prominence of soil-related issues in the AF research agenda is also a reflection of the overall prominence of soil research in the total research portfolio in all terrestrial land-use systems combined (agriculture, forestry, horticulture, grazing systems, etc.). Ever since the beginning of agricultural research (generally identified with the establishment of the Rothamsted Experiment Station, England, in the mid-1800s), soils and soil-related aspects including plant nutrition, have had a leading position in land-use R & D portfolio all over the world. Thanks to these efforts, soil science has developed into a well-researched and prominent discipline in the broad academic and scientific field and is endowed with a rich and voluminous literature base. Several comprehensive textbooks of soil science have been produced over the years; the currently popular ones with broad international appeal include N Brady and R Weil's *The Nature and Properties of Soils* (15th edition, Weil and Brady 2017; previous editions, e.g., Brady and Weil 2007), PA Sanchez's *Tropical Soil Management* (2nd edition, Sanchez 2019), and *The Encyclopedia of Soil Science* edited by R Lal, 3rd edition (Lal 2017). Another notable book is *The Ecology and Management of Forest Soils* (Fisher and Binkley 2000, and its multiple earlier editions) that is popular in forestry. Numerous other such publications focused on the soils of specific countries and regions are also available.

The fundamental aspects of soil science and principles of soil management are thus well established and are an essential part of the academic curricula of higher education in agriculture, forestry, and related disciplines around the world. It is neither necessary nor feasible to describe these in this context. Nevertheless, recognizing that several of those involved in agroforestry R & D may not be current on such fundamentals and also that it is important to have familiarity with these principles for understanding the issues, the common terms used in describing the nature, properties, and management of soils are explained here briefly. Although such explanations can be found in several textbooks and other resources, the authors of this book are convinced based on long years of their experience that asking a student or course participant to refer to some external sources other than the one being used as the main instructional resource is not as effective as having all the essential things grouped as one "bundle." Some such essential aspects including major properties and types of soils are described briefly in the following sections of this chapter. A summary of the terms and expressions that are commonly used in soil science and related fields is included. A good reference source for these terms is the *Soils Glossary* produced by the Soil Science Society of America (2020) (https://www.soils.org/publications/soils-glossary). Readers are encouraged to consult these, and other comprehensive literature sources referred to above for detailed information.

15.3 Soil Formation

15.3.1 How is the Soil Formed?

The soil that occurs on the land surface is a natural body consisting of solids (minerals and organic matter), liquids, and gases that can support rooted plants in a natural environment.

Soils are formed through a continuous process called weathering over millions of years, by which the original rocks and minerals on Earth's surface are transformed by physical disintegration and (bio)chemical decomposition. As represented by Hans Jenny's classical concept (Jenny 1941, 1980), **S = *f* (cl, p, o, r, t)**, which signifies that soil formation through weathering (S) is influenced by five major factors: climate (cl), parent materials (p), biota or living organisms (o), relief, slope, and landscape position (r), and time (t, duration or length of soil formation).

***Climate* (cl)**: Precipitation and temperature are important factors in soil formation. Soil forms most readily under warm conditions such as in the tropical and temperate regions. This physical weathering process is also impacted by rainfall, ice, and wind, and by the roots of higher plants, sometimes called biological weathering (Figure 15.1), and by the impact of animals. Chemical weathering processes also proceed fastest under warm conditions.

Figure 15.1 Biological weathering of soils: physical weathering of soil hastened by biological factors, such as the presence of tree roots in dried and cracked soils in arid regions. (Source: Chittaakorn59 – Shutterstock)

***Parent material* (p)**: Parent material includes different types of bedrock and glacial or stream deposits. When formed in place (i.e., if developed on the bedrock), soils are described as residual soils. Soils that develop on transported material (by gravity, water, ice, or wind) are sometimes referred to as "transported soil", although the soil itself is not transported.

***Biota or living organisms* (o)**: Organic material accumulates in wet locations where the plant growth exceeds the rate of residue decomposition.

***Relief, slope, and landscape position* (r)**: Soils develop best when the rate of soil formation is less than the rate of erosion. Therefore, steep slopes tend to have little or no soil. Also, topography influences the deposition of plant residues that form the parent material for organic soils.

***Time* (t)**: Soils, in general, take thousands of years to develop. The process is so slow that it is difficult to measure changes in soil formation over time. Residual parent materials generally have been subjected to weathering conditions for longer periods compared to "transported soil."

15.3.2 Soil Horizon and Soil Profile

A *soil horizon* is a layer of soil approximately parallel to the land surface, differing in properties (physical, chemical, and biological) and characterizations from the layers above and below it.

A *soil profile* is a vertical section of soil from the surface through all its horizons and extending into the C horizon (Figure 15.2).

15.4 Soil Properties

15.4.1 Physical Properties

Soil Structure describes the arrangement of the solid parts of the soil (sand, silt, clay) and the pore space located between them. Single particles when combined appear as larger particles or aggregates. They are held together by moist clay, organic matter, gums (from bacteria and fungi), and fungal hyphae.

Figure 15.2 Vertical section of a soil profile from the surface to the parent material

Soil Aggregates range from 0.002 mm to 2.00 mm. They can resemble various shapes such as granular, blocky, and crumb. These varied shapes allow for healthy soil to have pore spaces for air and water needed for healthy plant growth. Aggregates are formed through physical, chemical, and biological activities. Well-aggregated soils generally have greater soil health, ensure better agricultural productivity, and play a vital role in soil carbon sequestration.

Soil Texture refers to the proportions of sand, silt, and clay particles in the soil (Figure 15.3). The sand, loamy sand, and sandy loam groups are further subdivided depending on the proportions of sand present. The USDA (US Department of Agriculture) "soil texture triangle" (Figure 15.4) is used for determining the textural class of the soil based on the relative proportions of sand, silt, and clay. For example, a soil with 42% sand, 35% silt, and 23% clay is a "loam." A soil with 8% sand, 60% silt, and 32% clay is a "silty clay loam." Soil texture is also expressed qualitatively as "texture by feel." ***Soil texture*** and ***soil structure*** are both unique properties of the soil that will have a profound effect on its behavior, such as water holding capacity, nutrient retention and supply, drainage, and nutrient leaching.

Soil Color is derived from the minerals present in the soil as well as the organic matter content. For example, yellow or red soil indicates the presence of ferric iron oxides. Organic matter makes the soil color darker.

Soil Bulk Density is dependent on the mineral makeup of the soil and the degree of compaction. It is calculated as the dry weight of the soil divided by its volume (total volume of soil particles and the volume of pores between them, and hence the term "bulk density"). The high bulk density of soil is an indicator of low soil porosity and soil compaction.

How heavy is a soil?

A typical medium-textured mineral soil with a bulk density of 1.15 Mg m^{-3} weighs 1,250 kg m^{-3} (2,015 pounds per cubic yard)

A hectare furrow slice of a typical soil weighs ~ 2.2 million kg (~ 2 million pounds per acre)

15.4.2 Chemical Properties

Soil Reaction: Acidity, Salinity, and Alkalinity. The term soil reaction, although no longer used in soil science (Weil and Brady 2017), refers to its degree of acidity or alkalinity usually expressed as a pH value (range: 0–14), which is the measure of the hydrogen ion concentration of a solution with a pH of 7 indicating neutrality (neither acidic nor basic) (Figure 15.5). The pH of a soil solution is measured at a specified soil to solution ratio in a specified solution, usually distilled water, 0.01*M*

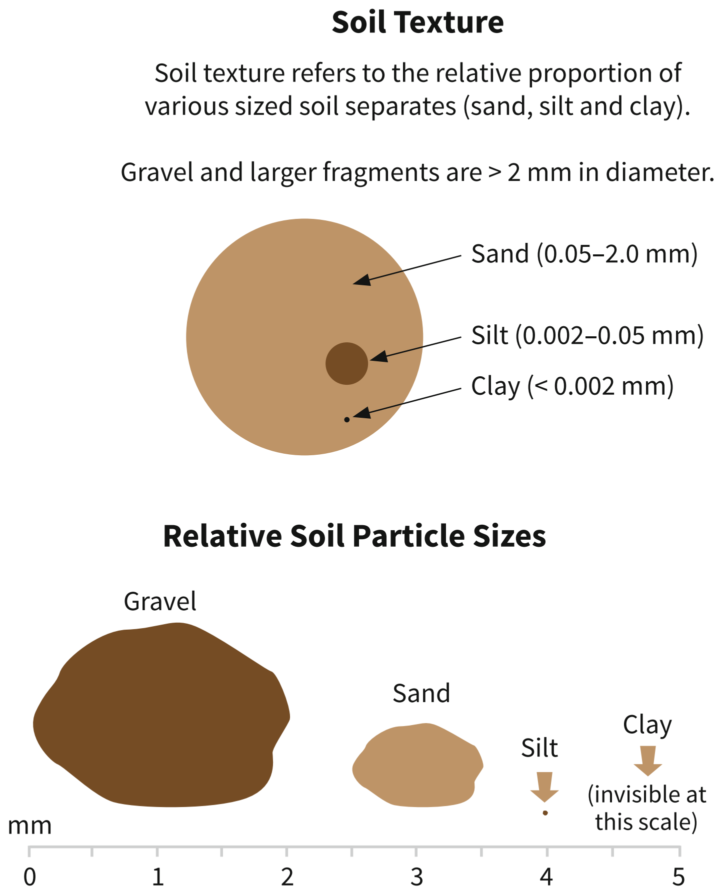

Figure 15.3 Relative proportion of soil particle sizes (sand, silt and clay). Reproduced from https://i.pinimg.com/originals/32/2b/04/322b0462355c74141cade1bfe72e6e2a.jpg

calcium chloride, or 1*M* potassium chloride. While the optimal soil pH range for most plants is between 5.5 and 7.0, many plants thrive at levels outside this pH range. Soil pH is important because it influences the availability of essential nutrients. Soil salinity refers to the amount of soluble salts in the soil; the process of increasing the salt content is known as salinization. Saline and alkaline soils contain relatively high contents of salts. Saline soil is nonsodic and does not contain sodium at levels that interfere with the growth of common crops but contains other soluble salts at levels sufficient to impair crop production, with the exchangeable sodium adsorption ratio < 15 and pH > 8.5. Alkaline soil has high levels of sodium to interfere with the growth of most crops, with an exchangeable sodium adsorption ratio > 15 and pH > 9.00.

Cation (and Anion) Exchange. Cation exchange is the exchange of ions between two electrolytes or between an electrolyte solution and a cation in the boundary layer between the solution and a negatively charged material such as clay or organic matter; anion exchange refers to the exchange of negatively charged ions. The ability of the negatively charged material to retain and release positively charged ions controls the mobility of the chemical species – such as potassium from fertilizers – in the soil solution.

The soil's **Cation Exchange Capacity** (CEC) is a soil's total capacity for holding exchangeable cations, which are positively charged ions – calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}). Anion exchange capacity (AEC) is the ability of a soil to adsorb or release anions from a soil. The soil exchange capacity is

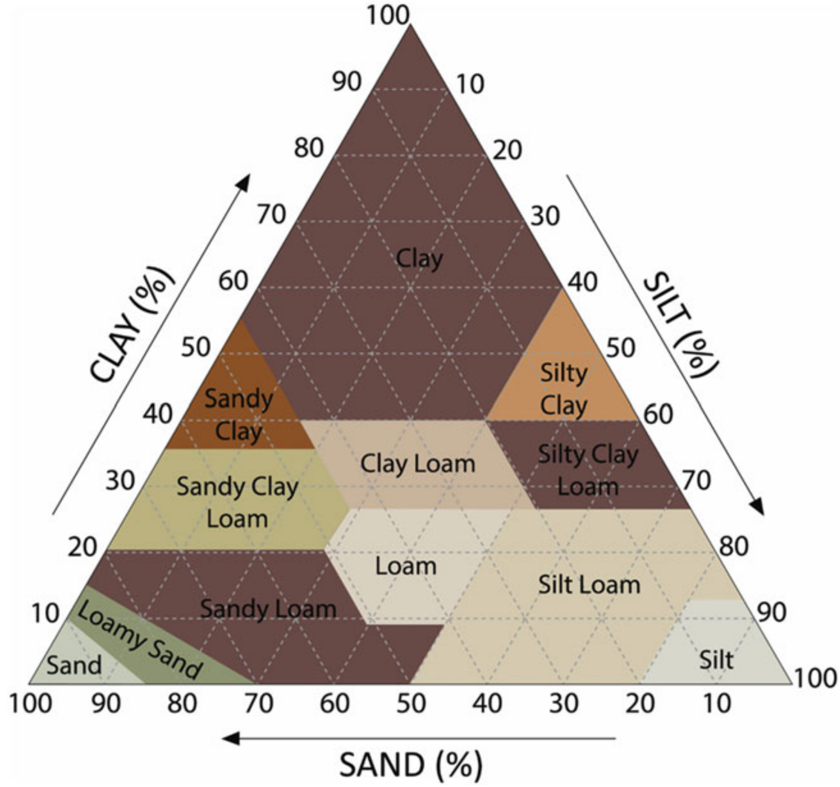

Figure 15.4 USDA Textural Classes as defined by the "textural triangle"

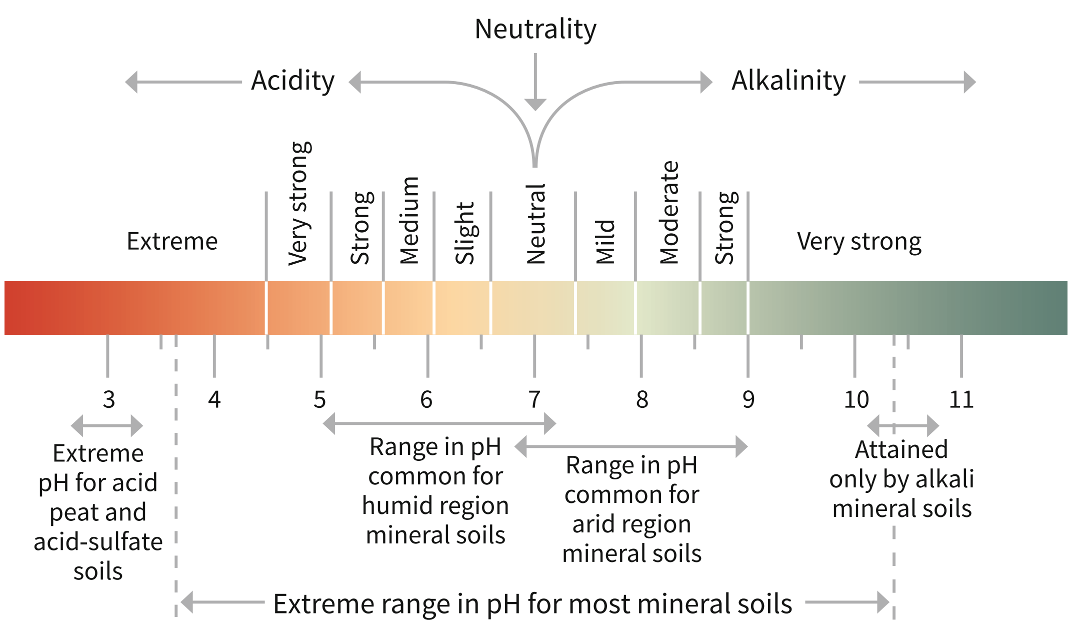

Figure 15.5 Range in pH for mineral soils including ranges commonly found in humid region and arid region soils. pH ranges: Very strongly acid, <4.5 – 5.0; Strongly acid, 5.1 – 5.5; Medium acid: 5.6 – 6.0; Slightly acid, 6.1 – 6.5; Neutral, 6.6 – 7.3; Alkaline, >7.3

therefore the total capacity of soil to hold exchangeable ions and thereby influences the soil's ability to retain nutrients.

Soil Colloids and Layer Silicates. The clay and humus particles that are extremely small and have colloid-like behavior are collectively called the **colloidal fraction**. These particles are about 1 µm in diameter and therefore have a large external surface area per unit mass, more than 1000 times the surface area of the same mass of sand particles. The silicate clays have an extensive internal surface area between their plate-like crystal units. The cations that are held on (adsorbed) by electrostatic attraction to negatively charged soil colloids are replaced by other cations through cation exchange**.**

Soils contain several types of colloids, such as crystalline silicate clays (e.g., kaolinite and smectite), non-crystalline silicate clays (e.g., allophane), iron- and aluminum oxides (e.g., gibbsite and goethite), and organic (humus) colloids. The crystalline silicate clays that are dominant in most soils are layered like the pages in a book and consist of sheets of closely packed and tightly bonded oxygen, silicon, and aluminum atoms. Depending on the number and arrangement of these "sheets," crystalline clays are classified into two main groups: 1:1 and 2:1 silicate clay. The 1:1 clay has one silicon and one aluminum sheet, and the 2:1 has two silicon sheets with one aluminum sheet in between. Kaolinite is the major type of 1:1 clay, and smectite (of which montmorillonite is the most prominent form) the major type of 2:1 clay in soils. The type of silicate clays in a soil has major influences on its physical and chemical properties.

Heavy Metals and Toxicity. Soils could become contaminated by the accumulation of heavy metals (lead, copper, arsenic, mercury, and zinc) released into the environment during disposal of industrial wastes, land application of fertilizers, and sewage sludge to name just a few sources. Such material could provide risks and hazards to humans (via contaminated food and water) and the environment. Agroforestry practices have a remarkable potential to remediate such soils (Chapter 22).

15.4.3 Biological Properties

The biological properties of soils arise from the soil biota that comprises large numbers of diverse organisms that live in them. These include microorganisms (such as bacteria, fungi, protozoa, viruses, and nematodes), mesofauna (collembola, mites, etc.), and macrofauna (earthworms, millipedes, termites, ants, beetles, and other invertebrates). It is estimated that 10–100 million organisms of more than 5000 taxa exist in just a handful of soil (Sanchez 2019). Together these organisms provide numerous essential ecosystem services that are critically important for humans and overall life on planet Earth. These include decomposition of organic matter, the transformation of plant nutrients, nitrogen fixation, soil structure regulation, and extension of plant root functions through mycorrhizal association. Soil microorganisms also include some plant and animal pathogens as well.

15.5 Soil Types and Soil Classification

Soils vary widely in their nature and properties. Farmers knew this for a long time, and they used to allocate different crops to soils depending on their judgment on crop – soil suitability, i.e., most suitable soil for a particular crop and the best crop/s suitable for a particular soil. Gradually, different descriptive terms emerged to designate soils according to their suitability for specific major crops (such as *black cotton soils* and *rice soils*) and on the parent materials of the soils (such as *limestone soils* and *alluvial soils*). The color and predominant textural composition of the soil have also been used for a long time to indicate the soil type; thus, terms such as *red soils, black soils,* and *sandy soils* are popular in common parlance even today. It is not unusual to hear the soil being referred to as "dirt," but such denigratory expressions can be dismissed outright as meaningless rants by the ignorant. While the various local terms used for limited purposes have their own value, they are inadequate for defining and comparing different soils and organizing the scientific knowledge that has been continuously becoming available.

As unbelievable it may sound, there is still no universally accepted soil classification scheme despite the tremendous advances that have been made in the field of soil science. This creates a strange situation that hinders "proper communication" (in terms of technical details) even among soil scientists from different parts of the world. Over the past several decades, several soil-classification schemes have been used around the world as described by Krasilnikov et al. (2009). The underlying concepts of these schemes are of two broad categories: soil genesis (soil formation with emphasis on how the soil has originated; Section 15.3.1) and soil morphology and properties (field observable attributes of the soil). Gradually, soils began to be classified and recognized as natural bodies, based not just on their color, location, or suitability for a specific crop or group of crops, but on their "individuality," i.e., profile characteristics. Thus, soils with similar properties at different locations can be classified similarly, and the research experience gained from one location can generally be used to predict the behavior of similarly classified soils from other locations. Based on these two major approaches to soil classification (soil genesis and morphology), two major systems of soil classification are currently used; the USDA Soil Classification (Soil Taxonomy) system (Soil Survey Staff 2014), and the United Nations-sponsored WRB system (World Reference Base) for Soil Resources (Bridges et al. 1998). Various national and regional classification schemes such as the European, French, Belgian, Brazilian, Indian, etc. that were in prevalence have now mostly been replaced by the UN-sponsored WRB system.

15.5.1 The USDA Soil Classification (Soil Taxonomy)

The USDA system of soil classification is a hierarchical system with six categories: order, suborder, great group, subgroup, family, and series. Twelve soil orders have been identified (Figure 15.6); their names and formative terms are given in Table 15.1, and the general degree of weathering and soil development for different orders are presented in Figure 15.7.

The orders and taxonomic properties often relate to Greek, Latin, or other root words with some relationship that explains the properties of the soil. The nomenclature of the different categories in the USDA-NRCS (Natural Resources Conservation Service) classification system is illustrated below using Mollisols, the highest percentage of ice-free land areas in the United States, and Entisols the highest percentage globally (Table 15.2) as examples.

Soil order: M*oll*isols
Suborder: Aqu*oll*s
Great group: Argioqu*oll*s
Subgroup: Typic Argioqu*oll*s

The "*oll*" identifies the lower categories as being a part of the M*oll*isols soil order.

The family name identifies subsets of the subgroup that are similar in texture, mineral composition, and mean soil temperature at a depth of 50 cm. Thus, the name **Typic Argiaquolls, fine mixed, mesic** identifies a family in the Typic Argioquolls subgroup with a fine texture, mixed clay mineral content, and mesic (18 to 15 °C) soil temperature (Weil and Brady 2017)

Soil order: Entisols. Several suborders exist in different parts of the world, e.g., i) Psamments (sandy; typical of the Saharan desert and Saudi Arabia, dominant parts of southern Africa and central and north-central Australia and also parts of the US), ii) Fluevnts (alluvial deposits; predominant in the intensively cultivated rice lands of Asia), iii) Orthents (typical; northern Quebec and parts of Alaska, Siberia, and Tibet), iv) Aquents (wet; flooded area around the Mississippi River). Entisol characteristics are highly variable and any generalization of agricultural management in these soils is difficult (Weil and Brady 2017).

15.5.2 The US Soil Taxonomy and UN (FAO/UNESCO) Soil Classification

The hierarchical organization of the US Soil Taxonomy is helpful – despite some initial difficulty

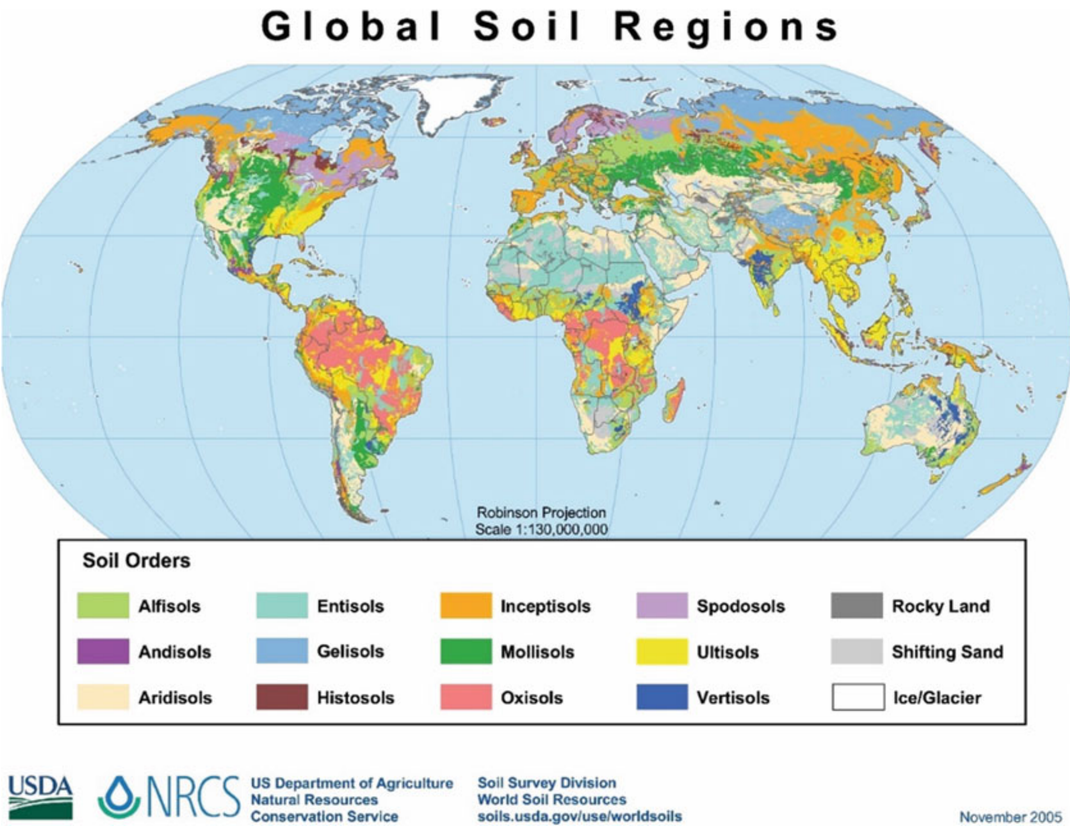

Figure 15.6 Global soil orders (USDA-NRCS 2005)

Table 15.1 Soil orders and their formative terms

Soil Order	Formative Terms
Alfisols	Alf, refers to Al and Fe
Andisols	Japanese, ando, dark
Aridisols	Latin, aridies, dry
Entisols	Ent, no specific meaning
Gelisols	Latin, gelare, to freeze
Histosols	Greek, histos, tissue
Inceptisols	Latin, inceptum, beginning
Mollisols	Latin, mollis, soft
Oxisols	French, oxide
Spodosols	Greek, spodos, wood ash
Ultisols	Latin, ultimus, last
Vertisols	Latin, verto, turn

in getting familiar with the terms – for examining relationships between different types of soils, where they are found, and what their properties and uses are. A USDA-NRCS soils map (USDA-NRCS 2005) is presented in Figure 15.6. This system of soil classification, although still not universally used, will be used in this book.

The other commonly used soil classification scheme is the WRB (World Reference Base; still sometimes called "the FAO Soil Classification").

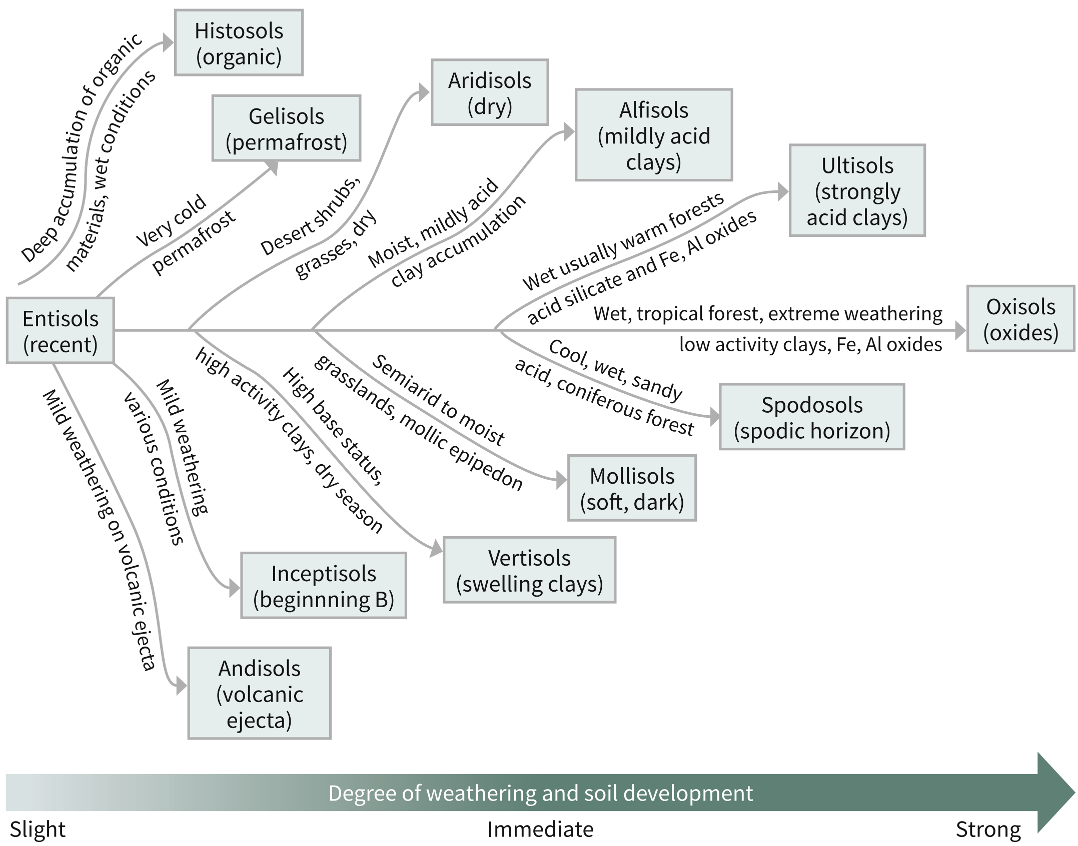

Figure 15.7 Diagram showing the general degree of weathering and soil development in the different soil orders classified in Soil Taxonomy. Also shown are the general climatic and vegetative conditions under which soils in each order are formed. Reproduced with permission from Brady and Weil (2008)

The United Nations Food and Agriculture Organization (FAO), in association with the U.N. Educational, Scientific, and Cultural Organization (UNESCO) prepared successive versions of a comprehensive *World Soil Map* during the 1970s. A revised legend was published in 1988. The World Soil Map was digitized and made available in 1995 (FAO/UNESCO 1995). The FAO legend was transformed into the WRB as a soil classification system with more quantifications, closely corresponding to the soil order categories, but not identifying all the suborders, of the Soil Taxonomy (Bridges et al. 1998, Deckers et al. 1998). Because of the international character of the FAO legend (WRB), it is widely used in many countries. Table 15.3 gives the approximate terms used for the major soil orders in the two soil classification schemes. Although the terms are somewhat equivalent, they are not readily interchangeable.

15.6 Plant Nutrients in Soils

Essential plant nutrients are those elements that are essential for the growth of all plants; i.e., without them, the plants would not grow. Of these, carbon (C), hydrogen (H), and oxygen (O) are taken up from air and water, and the rest from soils. Some other elements are taken up by some plants, but they are not essential for all, and therefore do not meet the criteria of essentiality. These include silicon (Si), selenium (Se), chromium (Cr), cobalt (Co), vanadium (V), and sodium (Na); some elements, which, if taken up in excess quantities could be toxic to plants (see Section 15.4.2, Heavy and Toxicity). Three elements [Nitrogen (N), phosphorus (P), and potassium (K)] that are needed by plants in relatively large quantities are called macronutrients. Calcium (Ca), magnesium (Mg), and Sulfur (S) are sometimes called secondary nutrients; these are needed by plants in relatively large quantities, but more than fulfilling their physiological functions in plants, they are also applied to soils in relatively large quantities as soil amendments to correct adverse soil conditions such as acidity and alkalinity. The other eight essential elements that are needed by plants in relatively very small quantities are called micronutrients. The various essential elements, their average concentrations in plants, and the ionic (or molecular) forms in which they are taken up by plants are shown in Table 15.4. A jingle that is commonly used to remember these 17 essential elements reads as follows: CHOPKiNS CaFe M(a)naged By Close C(o) uZ(i)n MoNi, that should sound like an easy-to-remember line "C Hopkins Café Managed by Close Cousin Moni."

15.7 Tropical Soils

Soil productivity is particularly relevant in the tropics where the soils are, in general, inherently poor and less productive (than in the temperate zones). Geographical distribution of soil orders in the tropical continents (Africa, the Americas, and Asia), based on the dominant soil in FAO maps is given in Table 15.2.

The highly weathered and leached acid infertile soils (Oxisols and Ultisols) that dominate the humid tropics constitute more than 40% of the tropical soils. Soils of moderate to high fertility (Alfisols, Vertisols, Mollisols, Andisols) constitute about 23%. Dry sands and shallow soils (Psamments, Entisols) and light-colored, base-rich acidic groups (Aridisols) account for about 17% of the tropical soils, and the remainder consists of various other soil groups.

The main soil-related constraints to plant production in these major soil groups of the tropics are summarized in Table 15.3. In general terms, Oxisols, Ultisols, and other highly weathered and leached soils have low exchangeable base contents, low nutrient reserves, high aluminum

Table 15.2 Approximate global land areas of different soil orders as percentages of the ice-free land, with their major land-uses and natural fertility status

Soil Order USDA Taxonomy	Global area		Tropical area		Major land uses	Natural fertility
	million hectares	%	million hectares	%		
Alfisols	1263	9.7	480	12.4	Crops, forest, range	High
Andisols	90	0.7	45	1.2	Tundra, forests, crops	Moderate to high
Aridisols	1578	12	186	4.8	Range, crops	Low to moderate
Entisols	2113	**16.2**	603	15.6	Range, forests, crops, wetlands	Low to moderate
Gelisols	1126	8.6	0	0	Tundra, bogs	Moderate
Histosols	153	1.2	32	0.8	Wetland, crops	Moderate to high
Inceptisols	1275	9.8	606	15.7	Forest, range, crops	Low to high
Mollisols	899	6.9	36	0.9	Forest, range, wetlands	High
Oxisols	981	7.5	962	24.8	Forests, crops	Low
Spodosols	336	2.6	6	0.2	Forest, crops	Low
Ultisols	1102	8.5	760	19.6	Forest, crops	Low to moderate
Vertisols	319	2.4	150	3.9	Crops, range, wetlands	High

Adapted from Sanchez (2019)

Table 15.3 Soil characteristics and classification according to US Soil Taxonomy and FAO Systems

US Soil Taxonomy	FAO	Description
Alfisols	Luvisols, Eutric, Nitosols, Planosols and Lixisols	Higher base status than Ultisols, but similar otherwise. Includes the more fertile tropical red soils. Dominant of west African subhumid tropics and savannas
Andisols	Andosols	Volcanic soils, moderate to high fertility, P fixation by allophane
Aridisols	Solonchak and Solonetz	Main limitation is moisture availability
Entisols	Various:	Young soils without A-B-C horizon development; generally high fertility except for sandy soils
Fluvents	Fluvisols	Alluvial soils usually of high fertility
Psamments	Arenosols and Regosols	Sandy, acid, infertile soils
Gelisols	Cryosols	Perennial frozen soils of the Artic and Antartica regions; also found at extremely high elevations in lower latitudes
Histosols	Histosols	Organic soils (> 20 % organic matter). Peat soils
Inceptisols	Various:	Young soils with A-B-C horizon development. Fertility highly variable
Aquepts	Gleysols	Poorly-drained moderate to high fertility
Tropepts	Cambisols	Well-drained Inceptisols (Dystropepts=acid, infertile; Eutropepts=high base status)
Mollisols	Chernozems	Black fertile soils derived from calcareous materials
Oxisols	Ferralsols	Deep, highly weathered, acid, low base status soils.
	Plinthisols	Excellent structure and good drainage. No significant increases in clay with depth
Spodosols	Podzols	Sandy surface horizon underlain with a horizon of organic and amorphous C, Fe and Al compounds. Acid and infertile
Ultisols	Acrisols, Dystric, Nitosols and Alisols	Similar to Oxisols except for a clay increase with depth.
		Similar chemical limitations. Textures from sandy to clayey
Vertisols	Vertisols	Dark heavy clay soils that shrink and crack when dry.
		Moderately high base status

Modified from Szott et al. (1991) and Nair (1993)
Note: Histosols are organic soils (as opposed to mineral soils) with ~1.2% occurrence globally

toxicity, low phosphorus availability, and high to medium acidity. These soils are called the Low Activity Clay (LAC) soils, indicating that their exchange complex is dominated by clay minerals with low cation exchange capacity (CEC), such as the 1:1 layer silicates of the kaolin group, and are therefore usually infertile. Ultisols can have larger problems with aluminum toxicity, whereas Oxisols are apt to be low in potassium, calcium, and magnesium; these soils also have high phosphorus fixation and hence low phosphorus availability. Spodosols and Psamments (sandy soils) are especially low in nitrogen, phosphorus, and bases. Although moisture availability is the most limiting factor to plant production in the dry (subhumid, semiarid, and arid) areas, low nutrient reserves could also be an equally serious problem (Szott et al. 1991).

Myths and misconceptions also abound about tropical soils, their nature, and productivity. For example, in many scientific and technical publications, tropical soils are described as or considered to be, universally infertile, and often incapable of sustained agricultural production. But such conjectures are not supported by scientific evidence. The Soil Science Society of America published a book (Sanchez and Logan 1992) in which leading soil scientists of the world discuss these widely-held misconceptions about tropical soils, and argue that several of the myths and misconceptions are based on inadequate information on principal soils of the region, the interaction between soils and prevalent climate, soil physical and mineralogical properties, soil chemical and nutritional characteristics, and soil microorganisms and their effect on soil

Table 15.4 The essential elements (plant nutrients), their average concentrations in plants and the form in which they are taken up by plants

Category of Essential Elements	Nutrient	Average concentration in plant biomass	Taken up as (ion or molecule)
Essential Elements	Carbon	45 %	CO_2
	Oxygen	40%	CO_2, H_2O, other ions
	Hydrogen	5%	H_2O
Macronutrients	Nitrogen	2.5%	NO_3^-, $NH_{4-}^{\ +}$
	Phosphorus	0.2%	H_2PO^{4-}, HPO_4^{2-}
	Potassium	1.75%	K^+
Secondary Nutrients	Calcium	1%	Ca^{2+}
	Magnesium	0.5%	Mg^{2-}
	Sulfur	0.3%	SO_4^{2-}
Micronutrients	Chlorine	100 ppm[a]	Cl^-
	Iron	100 ppm	Fe^{2+}, Fe^{3+}
	Manganese	50 ppm	MnO_4^{2-}
	Boron	30 ppm	BO_3^{3-}, H_3BO_3
	Zinc	20 ppm	Zn^{2+}
	Copper	5 ppm	Cu^{2+}
	Nickel	1 ppm	Ni^{2+}
	Molybdenum	0.1 ppm	MoO_4^{2-}

Adapted from Sanchez (2019)
[a]ppm = parts per million; corresponding SI unit = milligrams per liter

productivity. The main conclusions of this significant publication are:

- soils of the tropics are very diverse, their diversity being at least as large as that of the temperate zone;
- while it is true that rates of organic matter decomposition are higher and therefore it is more difficult to maintain organic matter levels in the tropical as compared to temperate soils, there is no difference in quality and effectiveness of humus in tropical and temperate soils;
- indeed, the soils of the tropics are generally poor in their fertility compared with temperate soils; however, the chemical processes involved in the maintenance of the soil's fertility and chemistry are the same regardless of latitude; what is different is their management, because of the different climate, crop species, and socioeconomic conditions found in the tropics;
- a vast majority of tropical soils are characterized by a weak structure prone to slaking, crusting, compaction, and a rapid loss of infiltration capacity; such weakly formed structural units slake readily under the impact of high-intensity rains, so that accelerated erosion is a severe hazard on most tropical soils with undulating to sloping terrain;
- factors such as rainfall pattern, rainfall intensities, potential evapotranspiration, waterlogging, temperature, and wind should be carefully considered while assessing soil productivity in the tropics;
- a delicate balance exists within the soil/plant continuum in the tropics; management practices that must include efficient use of fertilizers must be developed to sustain the productivity of this continuum; and
- many soils in the tropics do not contain indigenous rhizobial populations in adequate numbers to meet symbiotic N_2- fixation by leguminous crops.

15.8 Soil Health

The USDA-NRCS defines soil health as "**the continued capacity of soil to function as a vital living ecosystem that sustains plants,**

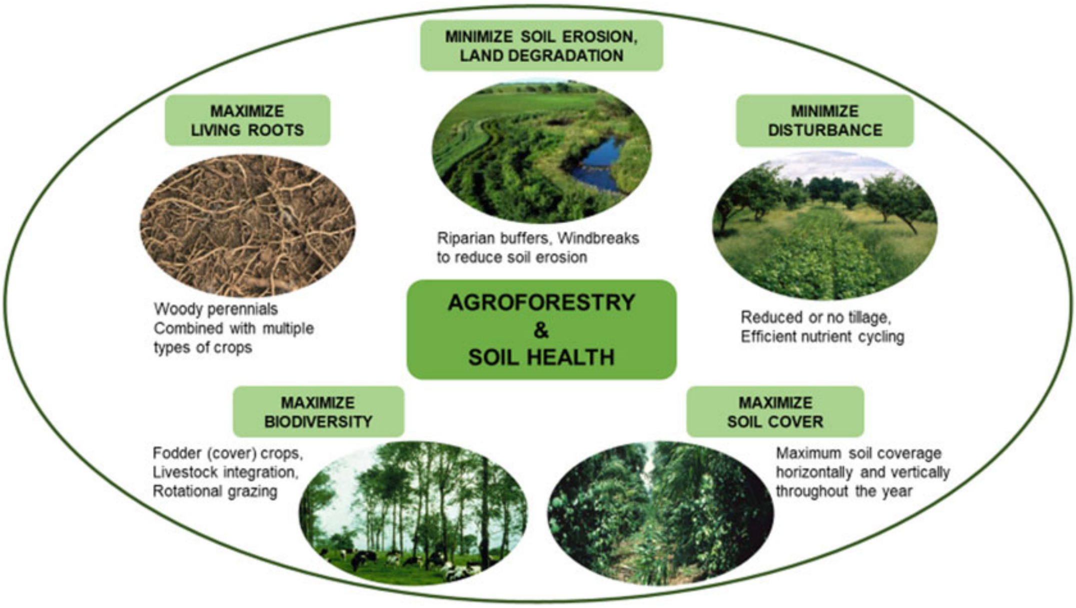

Figure 15.8 Agroforestry and Soil Health. The figure illustrates how the five key principles of soil health identified by USDA-NRCS are fulfilled by different representative examples of agroforestry practices. Source: Adapted from NRCS https://www.climatehubs.usda.gov/hubs/northwest/topic/soil-health-management-reduce-climate-and-weather-risks-northwest

animals, and humans" (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health**).** This definition highlights the importance of managing soils as a living resource so that they are sustainable for future generations.

Soil health is not a new concept; for example, Doran et al. (1996) have articulated the importance of soil health in sustainability. Wikipedia explains soil health "as a state of a soil meeting its range of ecosystem functions as appropriate to its environment," and that "in more colloquial terms, the health of soil arises from favorable interactions of all soil components (living and non-living) that belong together, as in microbiota, plants, and animals." Therefore, soil health cannot be defined in abstract quantitative terms. Because of that reason, soil health is explained in different ways, most of which arise from the perception that "Soil health is an indicator of how well the soil does what we want it to do."

Soil health has attained considerable significance lately in the context of the environment and climate-change discussions that have dominated the international arenas for the past two decades, wherein soils have been recognized as a potential sink for carbon and greenhouse gases. In this context, the role of tree-based land-management practices such as agroforestry is particularly relevant. Based on the USDA-NRCS portrayal of how different land-management practices fulfill the key principles of soil health, Figure 15.8 depicts how these principles are fulfilled by different agroforestry practices. Detailed discussions and illustrations of how each of these is fulfilled are presented in the subsequent chapters of the book.

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Soil Organic Matter (SOM) and Nutrient Cycling

16

Contents

Abstract

Recognized for long as the kingpin of agricultural soil management, soil organic matter (SOM) has attained added importance lately because of its significant role as a carbon sink. This chapter will focus on the issues related to SOM in soil productivity enhancement, which is of special relevance to the nutrient-depleted tropical soils; issues related to carbon storage for climate change mitigation and its environmental impacts that are of global significance will be discussed in separate chapters. One of the acclaimed roles of agroforestry is the potential benefit of soil improvement through the addition of nutrient-rich tree-and-shrub foliage (litter) to crop fields, which upon decomposition releases nutrients to the associated crops at critical stages of their growth. Numerous studies have been conducted since the 1980s to assess litter quality and nutrient-supplying ability of the foliage of various shrubs and trees used in tropical agroforestry systems (AFS), and the results have led to management recommendations under varying ecological conditions. Nutrient cycling, a related ecological process of major significance

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in AFS, refers to the continuous, dynamic transfer of nutrients in the soil-plant system. The principles of nutrient cycling and the role of woody perennials in enhancing it under AFS are briefly reviewed. Other issues included in the chapter are uptake of nutrients from the deeper soil horizons (the so-called deep capture of nutrients), and the role of tree biomass including roots in enhancing nutrient use efficiency. Also included in the chapter are some estimates and their underlying premises of the amounts of biomass (both aboveground and belowground) that will need to be added to the soil to maintain soil organic matter under AFS in the three major climatic zones of the tropics.

16.1 Introduction

Soil organic matter that is present in the surface horizons of the soil is a dynamic component that influences the soil properties and impacts the carbon balance in the agroecosystems at a scale highly disproportionate to its quantity. Already recognized for long as the kingpin of agricultural soil management, soil organic matter has attained added importance lately because of its significant role as a carbon sink and its high impact on the environment. This chapter will focus on the first of these two major roles, i.e., soil productivity enhancement. Given the perceived potential and importance of agroforestry systems in influencing organic matter dynamics and enhancing the productivity of nutrient-poor tropical soils, the focus of this chapter is on the tropics and subtropics. The second major role, i.e., carbon storage related to climate change and environmental aspects, which is of universal relevance, will be discussed in Chapter 20.

16.2 Soil Organic Matter

Soil organic matter (SOM, or simply OM) refers to all organic materials that are present in the soil. A vast majority of such materials are of plant origin; others include microbial tissues and dead biomass of soil fauna. Essentially, SOM consists of two parts: fully decomposed organic matter or humus that is already a part of the soil colloidal complex, and plant and microbial remains that are in various stages of decomposition, commonly called litter. Although the terms (plant) litter and biomass are often used synonymously in SOM discussions, they have different meanings in different contexts. In ecology, biomass refers to the amount of living matter in a given habitat, expressed either as the weight of organisms per unit area or as the volume of organisms per unit volume of habitat, whereas in energy parlance, biomass refers to organic matter, especially plant matter, that can be converted to fuel and is regarded as a potential energy source. In discussions related to SOM and soil fertility, the terms biomass and litter are used interchangeably. Most commonly, in such contexts, litter refers to plant biomass consisting of "prunings" obtained from harvesting (pruning) the hedgerows periodically as in tropical alley cropping (Chapter 6), fallen leaves and branches, and crop residues and roots that are added to the soil. Detritus is a term used in ecology to refer to discarded, dead, or decomposing bodies or fragments of organisms; in terrestrial ecosystems, it refers to leaf litter and other plant parts that are intermixed with soil, roughly the same as soil organic matter. The larger fragments of plant litter, including roots, contained in a soil sample are retained by the 2-mm sieve when the sample is prepared for laboratory analysis; such coarse litter is not counted as SOM. As time progresses, however, the coarse litter is broken down through microbial decomposition to finer particles that pass through the 2-mm sieve and become a part of SOM. Such partly decomposed plant fragments are called the light fraction of OM because they are of relatively lower density (<2.0 g cm^{-3}) and, therefore, can be separated by ultrasonic dispersion and flotation. The light fraction may hold substantial amounts (up to 25%) of plant nutrient reserves in the soil.

The role of SOM in soil fertility maintenance is well known. Extensive treatment of the subject can be found in standard soil science textbooks and other authoritative volumes (some of which are listed in the early part of Chapter 15). The discussions here will, therefore, be limited to some aspects related to trees and SOM that are rather unique to agroforestry systems, especially in the tropics. Most of the information presented here is synthesized from common textbooks and such other resources so that the literature citations are limited to a few. Other than the classical work of Nye and Greenland (1960) – reportedly the most cited work on soil fertility in the tropics – and such other widely applicable early studies, most of the research on organic matter dynamics and soil fertility improvement under tropical agroforestry systems *per se* were conducted during the 1980s and 1990s. Since the early 2000s when climate change became the "hot topic" for research involving soil carbon (see Chapter 20), there has been an almost total abandonment of soil-fertility-related research on agroforestry in the tropics, which explains why literature citations at the end of this chapter are mostly from the yesteryears.

Most of the knowledge on SOM is built up based on agricultural, single-species systems of herbaceous crops. Woody perennials differ from herbaceous crops in the rate and time of addition of organic materials, and the nature of the materials added. For example, there are usually specific peaks of organic-material addition as crop residues to the soil following harvesting of herbaceous crops, as opposed to somewhat continuous rates of addition from a tree-dominated system. Yet there are peaks and troughs of organic matter inflows even in such systems – peaks associated with pruning and litterfall seasons of deciduous trees and troughs of actively growing post-pruning and flushing seasons. Furthermore, trees provide far more woody and other lignified materials than herbaceous crops, which, in turn, affects the rate of decomposition and humus formation. See Chapter 20 for estimates of organic matter (carbon) addition to soils in various agroforestry systems in different parts of the world.

16.3 Organic Matter Decomposition

Decomposition refers to the conversion of litter to humus, which as mentioned in Section 16.2, is the fully decomposed organic matter that is already a part of the soil colloidal complex. Decomposition is an oxidation process by which the organic material is enzymatically broken down (oxidized) through the activity of soil biota – mainly bacteria and fungi – to carbon dioxide (CO_2) and water (H_2O) with concomitant release of energy. Decomposition also takes place under anaerobic conditions (without oxygen) but that is of relatively little relevance to agriculture. As a result of decomposition, the organic molecules are broken down to inorganic ions of plant nutrients (see Table 15.4 for a list of nutrients and their ionic forms) and released to the soil solution, and made available for plant uptake. This process by which plant nutrients held up in organic molecules are released as inorganic ions during decomposition is called mineralization; it happens simultaneously to decomposition but the two terms are not synonymous. Several authoritative books and other publications on these topics with special reference to tropics are available; Nye and Greenland (1960) and Swift et al. (1979) are particularly notable; more recent publications on the topic include Berg and Laskowski (2009); Prescott (2010); Berg and McClaugherty (2014).

16.3.1 Rates of Organic Matter Decomposition

Since the most widely accepted estimation of SOM is based on the determination of organic carbon (% organic matter = % organic C * 1.724), studies on organic matter are invariably studies of organic carbon. During the conversion of litter to humus, a loss of carbon occurs through microbial oxidation. The magnitude of this loss is highly variable and is often an unknown factor in carbon cycle studies. Nye and Greenland (1960) suggested a litter-to-humus carbon conversion of 10–20% for above-ground plant parts and 20–50% for root residues. This means the loss of C during the litter-to-humus conversion is 80–90% for aboveground plant parts and 50–80% for roots.

Even after the formation of humus, microbial oxidation causes a continuous loss of carbon. Since organic carbon is the source of energy or the substrate on which the microbes feed, their activity depends directly on the amount of carbon available at any particular time, and the amount of carbon so lost is proportional to that initially present. Thus, a relation exists between the initial carbon content (C_0), and the carbon content after one year (C_1):

$$C_1 = C_0 - kC_0, \text{or } C_1 = C_O\ (1 - k),$$

where k is the decomposition constant. Nye and Greenland (1960) estimated the decomposition constant values under shifting cultivation cycles as 0.03 (3%) under forest fallow and 0.04 (4%) under the cultivation phase. Usually, values of 5–10 % are reported for cultivated agricultural lands in the tropics (Nair 1994; Young 1989; Sanchez 2019).

The above equation and its rationale indicate a general pattern (Figure 16.1) of exponential decay of soil (humus) carbon of the form

$$C_t = C_0 \cdot e^{-kt}$$

where

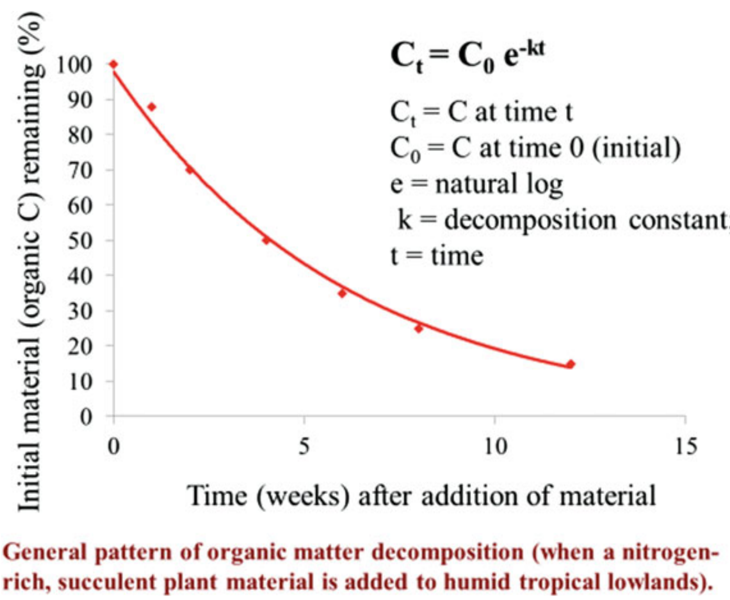
C_t = carbon after time t (years)
e = base of the natural log
k = rate constant, r

Based on this relation, the half-life of soil humus, i.e., the period within which half of the carbon in humus is oxidized, can be calculated as:

$$\textit{half-life} = (\textit{natural log of } 2/r) = 0.693/r$$

Carbon labeling (with ^{14}C) is widely used in SOM studies to detect at any time the amounts of ^{14}C-enriched plant residue remaining out of the total added to the soil. Based on such studies, Young (1989) presented the comparative patterns of C loss (i.e., OM decline) from soils in lowland humid tropics in southwestern Nigeria, the subtropical semiarid region of southern Australia, and the temperate region of England (Figure 16.2). While there was a rapid loss of carbon during the first 3 to 6 months in tropical soils (Nigeria), the time scale for carbon oxidation (loss) of the same magnitude was about four times longer in temperate soils (England), and about two times longer in the subtropics (southern Australia). This illustrates the general trend of the effect of climate on organic matter decomposition and explains why the tropical soils generally contain low levels of SOM compared to soils of subtropical and temperate regions, and why it is difficult to maintain high SOM levels in tropical soils.

Figure 16.1 Exponential decay of soil organic matter



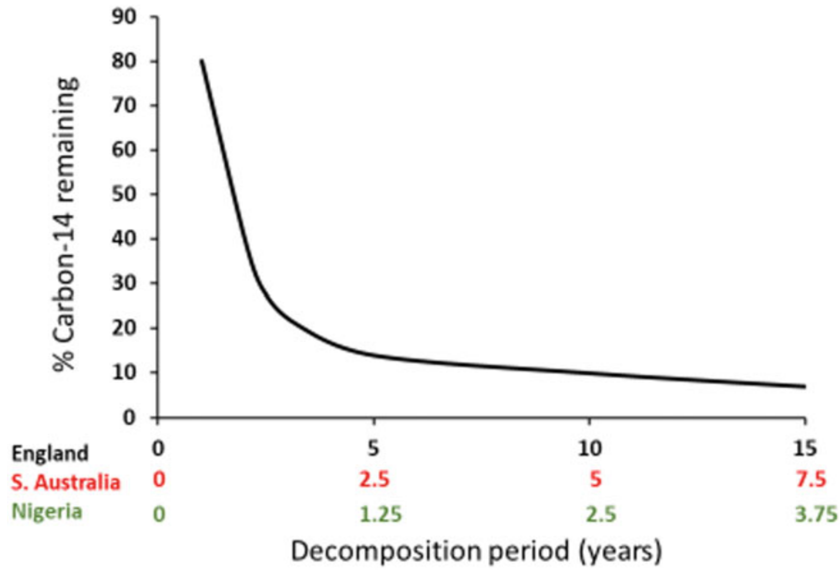


Figure 16.2 The general pattern of organic matter decay, derived from the loss of ^{14}C-labeled plant residues, in the tropical, subtropical, and temperate regions. (Source: Young 1989, cf. Nair 1993)

One of the most acclaimed roles of agroforestry in land management is the potential benefit of soil improvement, leading to improved crop production in nutrient-poor tropical soils under low-input farming conditions. In such situations, when the external application of nutrients through fertilizers is beyond the reach of many resource-poor farmers, agroforestry has indeed an important role to play. The nutrient-rich tree-and-shrub foliage (litter) can be applied to (placed in) crop growing fields and allowed to decompose and release the nutrients to the crop at critical stages of crop growth. Since organic matter decomposition is mediated by soil microorganisms, the rate of decomposition is dependent on environmental factors such as temperature, moisture, and soil conditions (especially pH) that influence the growth and activity of microorganisms. Furthermore, the composition of the material, referred to as litter quality, is a major factor that determines how fast the material decomposes.

16.3.2 Litter Quality

The term litter quality denotes the comparative "ease" of decomposition of the litter, "high-quality" and "low-quality" indicating those that decompose fast and slow, respectively. Litter quality is assessed based on two main factors: nutrient content especially nitrogen (N), and the type of organic (carbon) constituents. The typical composition of green plant materials is presented in Figure 16.3. Other conditions being similar, a plant litter that is high in N decomposes more rapidly than one that is low in N and is considered to be of high quality. Woody residues and other lignified materials such as cereal straw are more resistant to decomposition than succulent leaves because of not only their low N content but also high lignin content. The energy available to decomposer communities depends on the proportion of soluble C, cellulose, and hemicellulose, and lignin (Cadisch and Giller 1997), and the relative resistance (or ease, as the case may be) of the different components is presented in Figure 16.4. Soluble C includes metabolic and storage C and is primarily responsible for promoting microbial growth and activity (Smith 1994). Green foliage usually contains 20–30% soluble C. Cellulose and hemicellulose that constitute 30–70% of plant C (12–30% of total plant biomass) are structural polysaccharides of "intermediate" quality and are attacked by decomposer

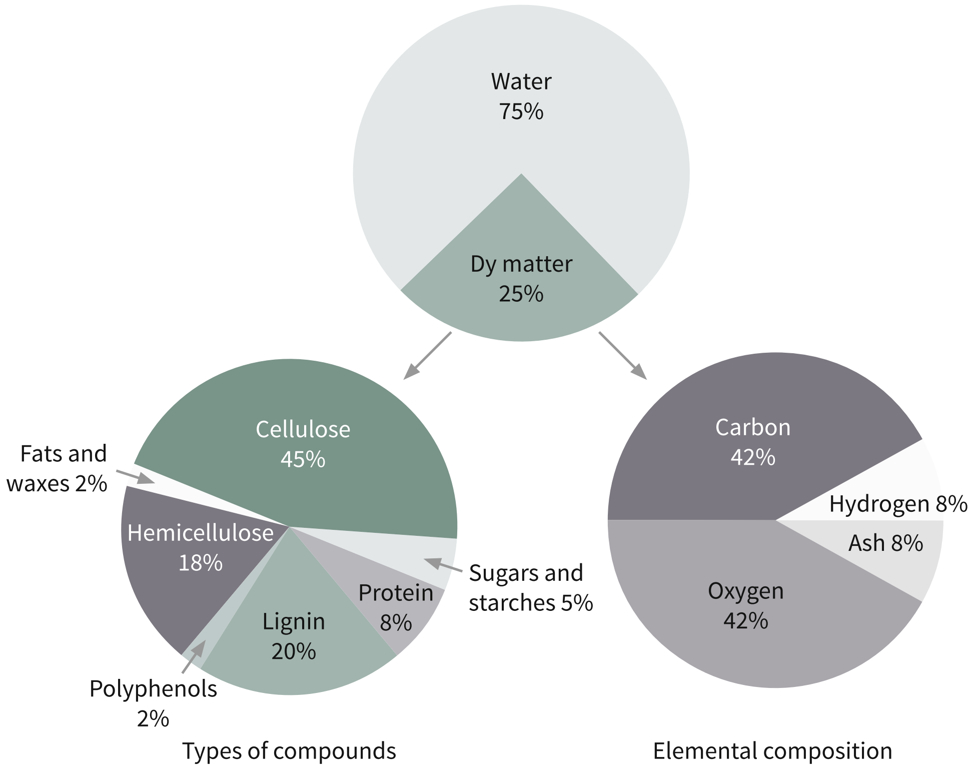


Figure 16.3 Typical composition of green plant materials, showing the major types of organic compounds on the left and the elemental composition on the right. "Ash" includes all constituent elements other than carbon, oxygen, and hydrogen. Source: Brady and Weil (2008)

Figure 16.4 Relative resistance of different plant constituents to decomposition

microbes after soluble carbohydrates have been depleted (Mafongoya and Nair 1997). Lignin, a constituent of the cell wall that physically protects cellulose and other cell-wall constituents from degradation is the "lowest" quality C constituent, which is most resistant to decomposition. Leaf litters of tropical agroforestry tree species contain 10–40% lignin (Figure 16.3; Table 16.1) (Constantinides and Fownes 1994; Mafongoya et al. 1997c), and lignin content is an important factor that determines litter decomposition rate (Jama and Nair 1996; Mugendi and Nair 1997). Thus, materials that are high in lignin and low in N are designated as "poor-quality" litter.

Polyphenols that constitute a relatively small percentage of organic materials in agroforestry tree species have a disproportionately larger effect on litter decomposition and N release (Palm and Sanchez 1990; Constantinides and Fownes 1994; Mafongoya et al. 1997b). Although polyphenols can serve as a C substrate for decomposer microbes, in general, they inhibit decomposer growth and activity (Swift et al. 1979). Condensed tannins or proanthocyanidins are the polyphenols most noted for their inhibitory effect by making the cell walls physically and chemically inaccessible

Table 16.1 Litter quality and decomposition: "Typical" composition of plant materials

Constituent	% Dry Matter
Cellulose	45
Hemicellulose	18
Lignin	20
Protein	8
Sugars and Starches	5
Polyphenols	2
Fats and Waxes	2

Carbon = 44%; Oxygen = 40%; Hydrogen = 8%; Ash = 8%
Source: Brady and Weil (2008) with permission

to the decomposer microbes, but there is no apparent correlation between total polyphenols (which can be as high as 5% in green foliage) and condensed tannins. Some tropical alley cropping species such as *Senna* (syn. *Cassia*) *siamea* have relatively high polyphenol content but low levels of condensed tannins (Jackson et al. 1996a, b) making their litter relatively easier to decompose, compared to that of species such as *Calliandra calothyrsus* that have high levels of both fractions (Handayanto et al. 1995) making it slower to decompose (Mugendi and Nair 1997; Mafongoya et al. 1997a, b). In laboratory incubation and field studies, Palm and Sanchez (1991a, b) found that legume leaves with high contents of soluble polyphenols (*Inga edulis* and *Cajanus cajan*) decomposed, and thus contributed nitrogen, less rapidly than those with low polyphenol contents (*Erythrina* sp.). Thus, although plant litter with an N content of more than 20 mg g^{-1} (2.00%) is generally considered to be of high quality, it can be altered by its lignin and polyphenol contents.

While several indicators of plant litter quality such as ratios of polyphenol to N, lignin to N, and polyphenol + lignin to N are reported to be useful, each may be valid for only specific situations and none may be universally applicable for all situations (Mafongoya et al. 1997b). The carbon to nitrogen (C:N) ratio is a rough indicator of plant litter quality that has stood the test of time despite its drawbacks. The main drawback is that unlike mineral fertilizers, the rates of nutrient release from which are predictable, the amount of N that will be released from a leaf litter upon decomposition is determined not just by its total N content but also by other determinants such as the contents of lignin and polyphenols, as discussed earlier. Nevertheless, the C:N ratio is still widely used. When a material of high (wide) C:N ratio is added to the soil, it provides a source of energy (C) for the microbes; consequently, the microbes multiply rapidly and draw upon the nutrient (N) reserves from the soil. Because the added material is low in N, this causes a temporary immobilization or unavailability of nitrogen for the plants. Subsequently, when the C (energy) source is depleted, the microbial population declines, and the N that had temporarily been incorporated in microbial tissues would once again be released to the soil and made available for plant uptake (Figure 16.5). That is how the addition of large quantities of low-quality litter to a standing crop in the field results in nitrogen deficiency for the crop, and conversely, how the addition of a high-quality litter promotes rapid crop-growth. In general, however, prunings that consist mostly of the leaves but also some woody tissues of many of the woody perennials used in tropical alley cropping are relatively high in nitrogen (Table 16.2). These prunings, when applied to the field, will result in increased available nitrogen levels for the associated crops, depending on their litter quality and decomposition rates. Mixing different plant litters of varying qualities has been suggested as a management strategy for regulating nutrient release from litters according to crop demand (see Section 16.4.3). Reviewing the research on mass-loss patterns, Gartner and Cardon (2004) reported changes in nutrient concentration and decomposer abundance and activity when leaves of different species are decaying in mixtures. They concluded that both non-additive and additive responses

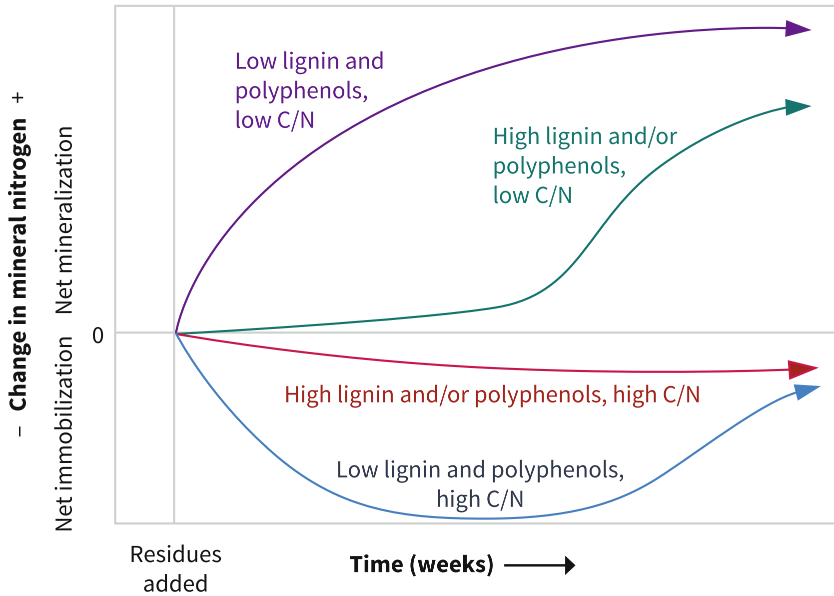


Figure 16.5 Influence of Litter Quality on nutrient mineralization and immobilization: temporal stock of nitrogen release from organic residues of varying C/N ratios and litter quality. Source: Brady and Weil (2008)

Table 16.2 Characteristics and leaf-litter-decomposition patterns of some multipurpose agroforestry trees

Tree Species	N_2-fixer	C:N ratio	Lignin content	Polyphenol content	Decomp. rate (relative)	% N released in first month	Reference[@]
Acacia angustissima	yes	18	+++	+++	slow	ND	5
A. auriculiformis	yes	20	++	+++	ND	immobilizes	1
Albizia (Samanea) saman	yes	14	+	+	fast	ND	6
[§]*Dactyladenia barteri*	no	25–30	++++	+++	slow	ND	9
Cajanus cajan	yes	10–15	+/++	+/++	moderate	ND	5, 6
Calliandra calothyrsus	yes	10–18	++	++++	slow	15–30	3, 5, 6
[§]*Croton macrostachyus*	no	14	++	++	ND	20	5
Erythrina sp.	yes	11	++	+	fast	25	7
Flemingia macrophylla	yes	19–25	++++	+++	slow	ND	5
Gliricidia sepium	yes	10–20	+	+	fast	35–60	1,2,3, 5, 6, 7
[§]*Grevillia robusta*	no	32	+++	++	slow	immobilizes	5, 6
Inga edulis	yes	14–19	+++	+++	slow	0–10	1, 8, 9
Leucaena leucocephala	yes	10–16	++	+++	fast	30	2, 3, 5, 6, 7

(continued)

Table 16.2 (continued)

Tree Species	N_2 fixer	C:N ratio	Lignin content	Polyphenol content	Decomp. rate (relative)	% N released in first month	Reference[@]
Peltophorum dasyrrachis	no	20	+++	ND	slow	12–15	2, 3
Senna reticulata	no	18	+	+	ND	0–20	5, 6
Senna spectabilis	no	14	+	+	moderate	ND	7
Senna siamea	no	16–18	+	++	moderate	immobilizes	1, 5, 8
Sesbana sesban	yes	15–16	+	+/++	fast	55	1, 5
Tephrosia vogelii	yes	15	+	+	ND	ND	8
[§]*Tithonia diversifolia*	no	14	+	+	ND	30	4, 5

[@]1. Constantinides and Fownes (1994); 2. Handayanto et al. (1997a); 3. Handayanto et al. (1994, 1995); 4. Mafongoya (1997a, b); 5. Oglesby and Fownes (1992); 6. Palm and Sanchez (1991a, b); 7. Tian et al. (1992a, b); 8. Tian et al. (1995)
[§]non-legumes; ND = no data
Direct values are not given due to difficulties in comparing results obtained with different analytical methods. Instead, the likely leaf qualities and the probable decomposition characteristics are given, based on extrapolation from data for fully opened leaves
A higher number of crosses (+) indicates a higher relative amount
Source: Adapted from Mafongoya et al. (1997b, c, 1998)

are probable in mixes compared to component species decaying alone, and mass loss often (though not always) increased when litters of different species are mixed (Figure 16.6).

The information on decomposition patterns of various tree litters has important management implications in deciding the schedule of hedgerow pruning and mulch application to crops. Annual crops have well-defined critical periods of high nutrient demand; if nutrients can be made available to the crops during this period, the efficiency of nutrient use will be enhanced; additionally, productivity will be increased and leaching losses reduced. Litter decomposition studies are, therefore, a common element of investigations on soil fertility aspects of agroforestry. The most common method is the so-called "litter-bag" technique described in standard laboratory and field manuals of ecology/soil science (e.g., Anderson and Ingram 1989). It consists of filling up a known quantity (usually 100 g) of the biomass (oven-dried plant material devoid of moisture) in litter bags (about 20 cm × 40 cm size, commercially available in forestry/ecology supply stores or can be made of permeable cloth), placing the bags 3–5 cm below the soil surface, retrieving the bags at pre-determined intervals (usually weekly or biweekly), rubbing off the soil adhering to the bag and cutting it open and retrieving the contents of the bag, drying it and determining the weight to get the loss on decomposition during that period. The dataset can be plotted to show the percentage of dry matter remaining (multiplied by 0.45 to get equivalent carbon content) against time to get the characteristic organic matter decomposition curve (Figure 16.1) reported in the voluminous literature on the subject. Several refinements to the above general procedure have been suggested.

Numerous reports on the results of field studies on litter decomposition studies are available from different parts of the tropics during the 1980s and 1990s, summarized by Nair et al. (1999). The widely accepted exponential pattern of litter (mulch) decomposition may follow a single smooth curve, as depicted in Figure 16.1. Budelman (1988) reported from Côte d'Ivoire that the *half-life* values of the fresh leaf biomass of *L. leucocephala*, Gliricidia sepium, and *Flemingia macrophylla* with C:N ratios of 12:1, 12:1, and 21:1, were 31, 22, and 53 days. As mentioned in Section 16.3.1, the half-life is calculated using a decomposition model of $Y_t/Y_o = 0.5$ where Y_t is the amount at time t and Y_o is the initial amount. Jama et al. (1995), investigating

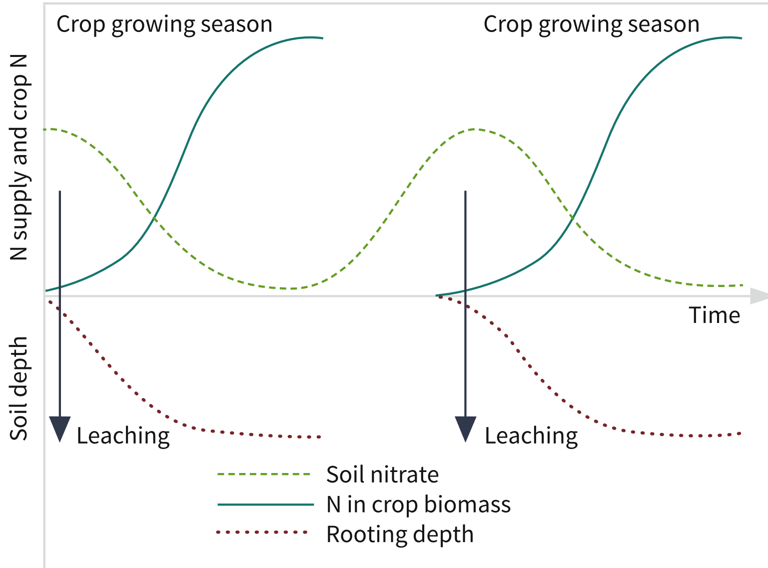


Figure 16.6 Schematic diagram of the lack of synchrony between soil-nitrate supply and crop demand that can lead to leaching loss of nitrate to soil below the crop-rooting zone.
Source: Buresh et al. (2004)

the decomposition patterns of mulches of *Senna* (syn. *Cassia) siamea* and *L. leucocephala* under semiarid conditions in Kenya found that, unlike the conventional decay curves relating remaining amounts of carbon (log scale) to time, where the decay curves are straight lines, the curves had two distinct parts: the first part of higher slope indicating a stage of rapid decomposition, followed by a part with much lower slope suggesting a low rate of decomposition. The duration of the first phase was about six weeks for *Leucaena* and ten weeks for *Senna*. The study showed that differences in decomposition patterns of different mulches could be explained in terms of the duration of the first phase: mulches with shorter first phases will have shorter half-life values than those with longer first phases. Half-life values and nutrient availability (including synchrony of nutrient release) that are important management considerations seem to be dependent on the pattern of the first phase of litter decomposition.

It is thus clear that fresh leaves of some tropical leguminous woody perennials such as *L. leucocephala, G. sepium*, and *Erythrina* spp. decompose relatively fast and release a major part of their nutrients (especially N) from the applied mulch within about four weeks under humid tropical conditions. In situations where a quick release of nitrogen is desired (as, for example, in cereal cultivation under conditions of little or no moisture limitation), these are good mulches. However, nutrient-rich, easily-decomposable material may not always be desirable because nutrient release may exceed plant nutrient demands resulting in asynchrony between supply and demands. Mulches of species such as *Senna siamea, F. macrophylla* and *Dactyladenia* (syn. *Acioa*) *barteri* that are also commonly used in tropical alley cropping are generally slow to decompose. In some situations, providing a good ground cover for a longer period, for example, to suppress weed growth or reduce moisture loss through evaporation from the bare soil surface, may be more desirable than providing a quick supply of nitrogen. In such circumstances, these slower-decomposing mulches are preferred (Wilson et al. 1986; Swift 1987; DeAngelis 1992; Young 1989; Jama et al. 1995).

The relationship of mineralization of other nutrients to mulch quality is reported to be similar to that of nitrogen. Potassium (K) release characteristics from the earlier mentioned study of Budelman (1988) showed that K release was fastest from *Leucaena*, followed by *Gliricidia*, and *Flemingia*; K contents of the three mulches were 1.52%, 1.52%, and 1.19%, respectively. In general, mineralization of P, K, Ca, and Mg is faster from high-quality *Erythrina* leaves than from those of *Inga edulis* or *Cajanus cajan.* Approximately 40% of the initial P and Ca contents and 75% of Mg and K contents of *Erythrina* leaves were mineralized within four weeks (Palm and Sanchez 1990; Szott et al. 1991a, b).

16.3.3 Synchronizing Nutrient Release with Plant Uptake

During the height of the Green revolution euphoria (the 1970s and 1980s), practically all research efforts in nutrient management for tropical crop production were focused on mineral fertilizers: determining the source, quantity, time and method of application, etc. of fertilizers, for best results. The importance of organic matter inputs such as tree litter (leaves, roots, byproducts, etc.), crop residues, green manure, farmyard manure, crop rotations, and intercropping – that used to be the mainstay of traditional agriculture, particularly in the tropics – was all but forgotten. With the coming of age of agroforestry as a land-management option in the late 1900s and gradual recognition of the importance of tree litter (used here as a collective term for all plant residues in agroforestry systems) in the maintenance of soil fertility from organic sources began receiving a fresh scientific look. The so-called synchrony hypothesis gained some prominence as a part of these efforts (Palm et al. 2001). Synchrony, in this context, refers to managing the rate of release of nutrients, primarily nitrogen, from decomposing organic inputs, especially aboveground litter, to synchronize with periods of maximum nutrient demand by crops such that crop growth is not adversely affected by the lack of readily available nutrients in optimum forms and quantities, and at the same time, the loss of released nutrients is minimized. The underlying principle of plant-residue management for ensuring synchrony is the differential rates of decomposition of plant residues depending on their litter quality. The application of a mixture of litters of different qualities rather than a single type of litter offers a practical way of exploiting this principle. In support of this approach, Palm et al. (2001) and Chivenge et al. (2011) proposed categorizing litters (also called organic resources – OR) into four categories depending on their N, lignin, and polyphenol contents, and applying a mixture of litters according to crop demand as presented in Figure 16.7. Low-quality litters that are high in lignin will result in a low net mineralization and

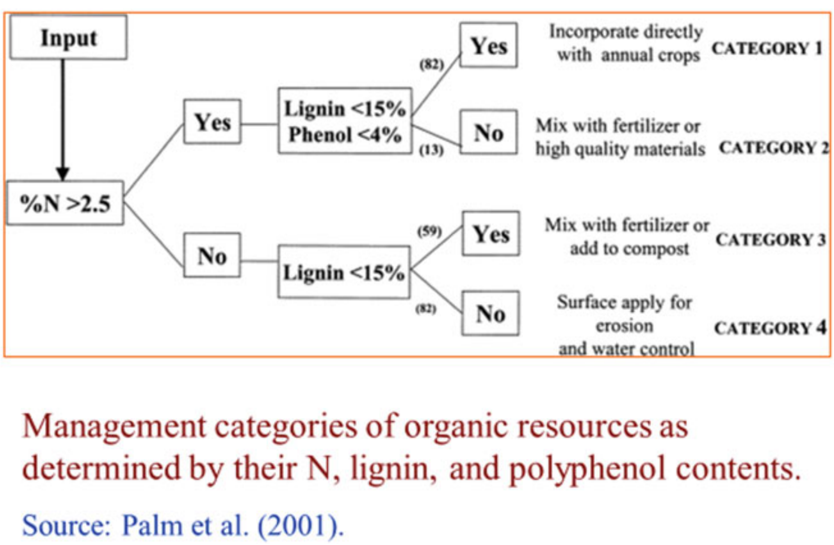


Figure 16.7 Recommendations on mixing plant of litters of different quality for optimum decomposition in soil fertility management

plant uptake in the first cropping season but will produce a greater residual effect in subsequent seasons, whereas litters of "intermediate quality" that are high in tannin exhibit delayed nutrient release but will release nutrients rapidly after a lag period. Under conditions where significant leaching or denitrification occurs, plant uptake of mineral N applied at planting can be increased by simultaneous application of low-quality litter, leading to a temporary immobilization of N during early stages of crop growth but re-mineralization of N later. Thus, better synchrony and, hence nutrient use efficiency, can be accomplished through management decisions such as selecting species with differing rates of litter decomposition, adjusting the timing of pruning to regulate the time of addition of the mulch, and modifying the method of application of the mulch (surface addition or soil incorporation). Despite its scientific appeal, reports on field-level adoption of these suggestions to any significant extent are not available.

16.4 Nutrient Cycling

16.4.1 The General Concept of Nutrient Cycling

In a soil-plant system, plant nutrients are in a state of continuous, dynamic flux. The plants take up nutrients from the soil and use them for metabolic processes. Some of the plant parts such as dead leaves and roots are returned to the soil during the plant's growth, and, depending on the type of land use and the nature of plants, plant parts are added to the soil when the plants are harvested. The litter or biomass so added decomposes through the activity of soil microorganisms, and the nutrients that had been bound in the plant parts are released to the soil where they become available to be taken up by plants once again. Nutrient cycling, especially as used in most agroforestry discussions, refers to this continuous, dynamic transfer of nutrients in the soil-plant system, such as a farmer's field (Nair et al. 1995; Buresh and Tian 1997). In a broader sense, nutrient cycling involves the continuous transfer of nutrients within different components of the ecosystem and includes processes such as weathering of minerals, activities of soil biota, and other transformations occurring in the biosphere, atmosphere, lithosphere, and hydrosphere (Jordan 1985).

Numerous schematic drawings of nutrient cycling are available (for example, a simple web search will bring out numerous results). A general and simple model of nutrient cycling in a tree-based ecosystem consists of the soil-plant system, which could be considered to consist of several compartments. The crown surface forms the boundary of the system; this is where the input of bioelements (i.e., elements that are biologically important) occurs through wetfall (precipitation) and/or dryfall during periods devoid of precipitation. The soil surface is the entry point for inputs into the soil compartment. The surface soil layer is the zone of intensive root-activity, whereas the subsoil constitutes the extensive root-activity zone. The deeper limit of the extensive root layer is the boundary between the ecosystem and the hydrosphere and lithosphere, and the bioelements transported beyond this layer are considered as lost from that ecosystem.

Nutrients taken up by the plant are either "stored" in plant parts or used for the production of non-storage organs. Fertilizer application initially results in the input of nutrients and accompanying ions into the solid phase of the uppermost layer of the soil. Depending on the water content of the soil and the solubility of the fertilizers, they pass into the solution phase of the same soil layer and then enter the plant compartment of the system via uptake. Based on the flow rate of percolating water and the soil properties, some parts of the nutrients that are in the soil solution are washed out of the nutrient-absorbing zone, and this represents a loss (output) from the system. Dissolved nutrients, especially ions like nitrate, which do not significantly interact with the soil matrix (i.e., are not "held" by it), have a greater likelihood of being so "lost." Phosphates, which possess low solubilities or are transformed into compounds of low solubility, are generally less affected by leaching or percolation loss, and the magnitude of the loss of cations like potassium depends on the exchange capacity of soils.

The total amount of nutrients involved in nutrient cycling depends on several factors. Ecosystems composed predominantly of trees characteristically contain large quantities of living biomass (including wood) and therefore, a large inventory of chemical elements. Roots are estimated to constitute 20–30% (and more in drier climates) of the total living biomass of the trees, and there is a constant addition of organic matter to the soil through dead and decaying roots (e.g., fine root dynamics). Besides, there can be significant additions of soil organic matter during active root growth in the form of sloughed-off tissues and exudation of organic compounds. Much of it comes directly from the roots without the intervention of soil microfauna and represents a steady release of carbohydrate-rich organic material from actively growing roots, and, thus, an energy input into the soil ecosystem capable of supporting a substantial microbial population. The major recognized avenue for the addition of organic matter to the soil (and, hence, of nutrients to the soil from the trees standing on it), however, is through litterfall, that is, through dead and pruned or falling leaves, twigs, branches, fruits, etc. (Section 16.3).

Nutrient cycling occurs to varying degrees in all land-use systems. Agroforestry and other tree-based systems are commonly credited with more efficient nutrient cycling (and, in turn, a greater potential to improve soil fertility) than many other systems because of the presence of woody perennials in the system and their suggested beneficial effects on the soil (Section 16.5). Generally, these woody perennials have more extensive and deeper root systems than herbaceous plants and thus have the potential to capture and recycle a larger amount of nutrients. Their litter contribution to the soil's surface is also greater than that of herbaceous plants.

Nutrient cycling has been a rigorous and prolific area of investigation in forest ecosystems during the 1970s and 1980s including tropical systems, and numerous reports are available. A good synthesis of such old reports is provided by Waring and Schlesinger (1985). The results of these nutrient cycling studies in forest ecosystems may not be of direct relevance to agroforestry systems, because compared to forest ecosystems, agroforestry systems are subject to more frequent disturbances caused by management practices such as pruning and soil tillage.

16.4.2 Nutrient Cycling in Agroforestry Systems

Natural forest ecosystems of the tropics, which are the results of natural selection over long periods, represent self-sustaining systems with efficient nutrient cycling. These are "closed" nutrient-cycling systems with relatively little loss or gain of the actively cycling nutrients and high rates of nutrient turnover within the system. In contrast, most agricultural systems represent "open" or "leaky" systems with comparatively high nutrient losses. A managed land-use system that "mimics the structural and functional complexity" of natural ecosystems, comes in between these "extremes" and is likely to be more sustainable than most agricultural systems (Nair 1995; Ewel 1999). The major difference between agroforestry and other land-use systems lies in the transfer or turnover of nutrients from one component to the other, and the possibility of managing the system or its components to facilitate increased rates of turnover without affecting the overall productivity. Results from several studies support this view.

A generalized model of nutrient cycling in an agroforestry system in comparison to that of monocultural agricultural and forestry systems, originally proposed by Nair (1984), is presented in Figure 16.8. Apart from species composition, the major difference between agroforestry and the other production systems (agriculture and forestry) is the greater possibility for managing the components of AFS (agroforestry systems) to facilitate increased rates of nutrient turnover within different compartments of the system (Nair et al. 1995). A major research thrust in agroforestry during the late 1990s was to understand the processes involved in such nutrient

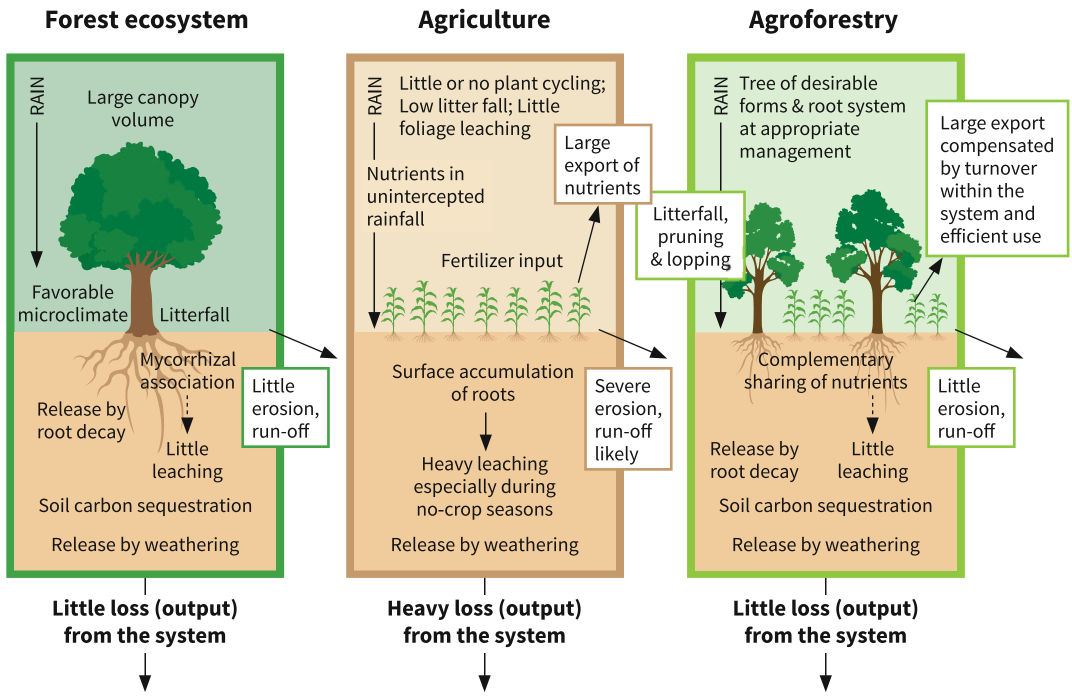


Figure 16.8 Schematic representation of nutrient cycling and management in an agroforestry system in comparison with common forestry and agricultural systems. Source: Adapted from Nair (1984)

transfers under a variety of conditions (Sanchez 1995; Rhoades 1997; Buresh and Tian 1997; Mafongoya et al. 1997a; Khanna 1997; Young 1997). These efforts led to the identification of three main tree-mediated processes/pathways that determine the extent of nutrient cycling in AFS:

1. Enhanced availability of nutrients resulting from production and decomposition of tree biomass
2. Increased input of nitrogen to the system through biological nitrogen fixation (BNF) by nitrogen-fixing trees (NFT) used in AFS
3. Greater uptake and utilization of nutrients by tree roots from deeper layers of soils that are not reached by crop roots in crops-only systems.

The first and third of these three aspects will be considered in this chapter; the second (BNF) will be discussed in the following chapter (Chapter 17).

16.4.3 Management of Litter Decomposition for Nutrient Use Efficiency

The understanding of the synchrony concept and importance of litter quality on litter decomposition patterns (Section 16.3.3) has led to the development of management strategies for improving the efficiency of uptake and utilization of nutrients in simultaneous agroforestry systems in the tropics. Unlike in natural and agricultural systems where senescent materials constitute the bulk of plant biomass input to the soil, green foliage constitutes the bulk of such inputs to AFS. These two types of litters differ considerably in quality and, therefore, in their decomposition rates. While mobile nutrients are re-translocated from senescent leaves to younger parts of the plant before senescence (resorption) or leaf fall (Constantinides and Fownes 1994), no such translocations occur in the case of pruned materials. Moreover, nutrient deficiency, especially of N, during plant growth can enhance the polyphenol content in leaves. For example, Handayanto et al. (1995) produced litters of *C. calothyrsus* and *G. sepium* of varying quality by altering N supply to the plants. Exogenous N supply to the plants resulted in increased N concentration and reduced polyphenol content of the leaves and resulted in faster litter decomposition and uptake of released N by maize plants (Handayanto et al. 1997a, b). Thus, better-quality leaf biomass could be expected from plants growing in association with N_2 fixing species (Chapter 17) compared to those growing under N-deficient conditions.

Many leguminous trees used in AFS such as tropical alley cropping produce substantial quantities of biomass (Table 16.3) containing relatively high concentrations of the major nutrients (Table 16.4). Following biomass decomposition, the nutrients, especially N, in the biomass are recycled and made available to support crop growth (Palm 1995; Table 16.5). Nutrient recovery is the term used to indicate the extent to which such nutrients are taken up by the current (and subsequent) season's crop. The reported nutrient recovery rates by the current season's crop are highly variable, ranging from 10% to more than 40% (Haggar et al. 1993; Handayanto et al. 1994; Palm 1995; Mafongoya and Nair 1997). In subhumid Kenya, Mugendi et al. (2000), using ^{15}N tracer, found that only 9–13% of the initial ^{15}N was recovered by the first (current) season's maize crop while 55–69% was found in the soil organic matter pool after the maize cropping season, and the remaining 20–30% of the initial ^{15}N could not be accounted for (Table 16.6). Haggar et al. (1993) also found that the amount of N left in the soil after the first crop was as high as 80% of the initial N in the tree biomass. These studies indicate that a considerable amount of N added as tree biomass to the crop production field may be retained in SOM.

Comparing the effects of *L. leucocephala* fallow versus a bush fallow on selected chemical properties of an Alfisol in western Nigeria for three years, Juo and Lal (1977) found that the cation exchange capacity and levels of exchangeable calcium and potassium were significantly higher in the *L. leucocephala* fallow than in the bush fallow. However, MacDicken (1991) reported from his studies in Occidental Mindoro, The Philippines, that soil pH in the 0–10 cm depth was significantly higher under a natural bush fallow compared with an improved fallow planted with *L. leucocephala;* he attributed this to increased extraction of Ca from lower soil depths and its deposition on the upper layers under the bush fallow ("nutrient pumping": see Section 16.5.3). The results of several years of investigations on the acid soils (Ultisols: Typic Paleudults) of Yurimaguas in the Amazon basin of Peru showed that managed leguminous fallows significantly increased soil nutrient (N and P) levels (Szott et al. 1991a), while Agamuthu and Broughton (1985) showed that nutrient cycling in oil-palm plantations where leguminous cover crops (*Centrosema pubescens* and *Pueraria phaseoloides*) were used was more efficient than in plantations where there was no cover crop. The loss of nitrate-nitrogen through leaching was also significantly lower in the former system, indicating that the improved cycling was perhaps due to the presence of the leguminous species, irrespective of whether it was woody or non-woody, and not of the woody perennial, *per se*.

In shaded-perennial crop systems too, N transfer from N_2-fixing leguminous shade trees to non-N_2-fixing associated crops is assumed to occur through the decomposition of the aboveground biomass added to soil following shade-tree pruning and litterfall (Fassbender 1993; Table 16.7). In shaded cacao and coffee plantations of Latin America with 120 to 560 leguminous shade trees per hectare pollarded up to three times per year, these inputs were estimated as ranging from 3 to 14 Mg ha^{-1} yr^{-1} dry matter with 6–340 kg N ha^{-1} yr^{-1} (Beer 1988). Nygren and Ramirez (1995) found a turnover of 6.8 to 35.4 g N per tree in a 23-week pruning cycle, equivalent to 9.6 to 50.0 kg N ha^{-1} yr^{-1} through the senescence

Table 16.3 Biomass production by some tree species used in alley cropping and biomass transfer systems in the humid, subhumid, and semiarid zones of the tropics

Site description (rainfall: mm yr^{-1})	Species	Trees ha^{-1}	Tree age (months)	Prunings (number yr^{-1})	Dry matter (Mg ha^{-1} yr^{-1})	Ref
Hyderabad, India; rainfall 750; Alfisols; pH 7.0, P = 8 ppm (Olsen)	*Leucaena leucocephala*	2000	48	ND[a]	1.4 (l)	1
		833	48	ND	7.4 (l+w[b])	2
Ibadan, SW Nigeria; rainfall 1280; Alfisols; pH 6.2, P = 25 ppm (Olsen)	*Leucaena leucocephala*	10 000	36	6	6.5 (l)	3
Yurimaguas, Peru; rainfall 2200; Ultisols; pH 4.2–4.6, P = 8 ppm (Olsen)	*Inga edulis*	8888	11	3	9.6 (l+w)	4
	Gliricidia sepium 14/84	5000	11	3	8.1 (l+w)	
Onne, SE Nigeria; rainfall; Ultisols; pH 4.0, P = 50 ppm (Bray)	*Acioa barteri*	2500	48	ND	13.8 (l+w)	5
	Alchornea cordifolia	2500	48	ND	14.9 (l+w)	
	Senna siamea	2500	48	ND	12.2 (l+w)	
	Gmelina arborea	2500	48	ND	12.3 (l+w)	
Sumatra, Indonesia; rain 2575; Oxisols, pH 4.1, P = 4.8–6.8 mg kg^{-1} (Mehlich 1)	*Paraserianthes falcataria*	19 900	09	4	4.9 (l+w)	4
			21	4	9.7 (l+w)	
	Calliandra calothyrsus	19 900	09	4	6.8 (l+w)	
			21	4	10.7 (l+w)	
	G. sepium	10 000	09	4	0.6 (l+w)	
			21	4	1.4 (l+w)	
Costa Rica; rainfall 2640; Inceptisols; pH = 4.3–4.8; P = 15 ppm (Olsen); N = 0.25 g $100g^{-1}$	*G. sepium*	6666	24	2	9.6 (l+w)	6
			60	2	15.2 (l+w)	
	Erythrina poeppigiana	555	24	2	7.4 (l+w)	
			60	2	11.1 (l+w)	
Western Samoa; rainfall 3000; moderately fertile, Inceptisol; no soil data	*Calliandra calothyrsus*	5000	48	3	12.1(l+w)	7
		3333	48	3	7.6 (l+w)	
	G. sepium	5000	48	3	10.7 (l+w)	
		3333	48	3	6.5 (l+w)	
Embu, Kenya; rain = 1500 mm yr^{-1}; pH 5.5, P = 7 mg kg^{-1} (Olsen); N = 0.25 g $100g^{-1}$	*Calliandra calothyrsus*	4444	48	2	4.0 (l)	8
	L.leucocephala	4444	48	2	3.9 (l)	
Chitedze, Malawi; rainfall 750–785 mm yr^{-1}; Alfisols; pH 5.7; P = 2.4 mg kg^{-1} (Olsen), N = 0.18%	*Leucaena leucocephala*	ND	60	2	3.1 (l)	9
Machakos, Kenya; rainfall 700; Alfisols; pH 6.0–6.5; P = 10–16 mg kg^{-1} (Olsen), N = 0.08%	*Senna siamea*	11 111	60	2	3.1 (l)	10
	L. leucocephala	2998	48	4	2.2 (l)	11

[a]ND = not determined. [b] l = leaves and green shoots; w = woody material

Source: Updated from Fernandes et al. (1994)

References: 1. Singh et al. (1989); 2. Hocking and Rao (1990); 3. Kang et al. (1981); 4. Szott et al. (1991a, b); 5. Ruhigwa et al. (1992); 6. Kass et al. (1989); 7. Rosecrance et al. (1992); 8. Mugendi and Nair (1997); 9. Xu et al. (1993); 10. Mugendi et al. (1999a, b); 11. Jama et al. (1995)

Table 16.4 Nutrient concentration of some multipurpose tree prunings in tropical agroforestry systems

Tree species	Nutrient concentration (%)				Source
	N	P	K	Ca	
Alchornea cordifolia	3.29	0.23	1.74	0.46	Kang et al. (1984)
Cajanus cajan	3.60	0.2	n.a	n.a	Kang et al. (1984)
Senna siamea	2.52	0.27	1.35	n.a	Yamoah et al. (1986a, b)
Dactyladenia barteri	2.57	0.16	1.78	0.90	Wilson et al. (1986)
Erythrina poeppigiana	3.30	0.18	1.16	1.52	Russo and Budowski (1986)
Gliricidia sepium	4.21	0.29	3.43	1.40	Kang et al. (1984)
Inga edulis	3.1	0.20	0.9	0.7	Szott et al. (1991a)
Leucaena leucocephala	4.33	0.28	2.50	1.49	Kang et al. (1984)

n.a = not available

Table 16.5 Comparison between nutrient requirements of a maize crop[a] and nutrient addition by some multipurpose tree (MPT) leaves[b]

MPT Species	Nutrients, kg ha^{-1}				
	N	P	K	Ca	Mg
Leucaena leucocephala	154	8	84	52	13
Erythrina poeppigiana	132	7	46	61	
Inga edulis	127	9	50	30	7
Senna siamea	105	6	44	110	7
Dactyladenia barteri	60	4	31	40	8
Grevillea robusta	52	2	24	60	7
Crop requirement	**80**	**18**	**66**	**15**	**10**

[a]A maize crop yielding 2 Mg ha^{-1} grain and 3 Mg ha^{-1} stover
[b]MPT leaves at the rate of 4 Mg ha^{-1} per cropping season
Source: Adapted from Palm (1995)

Table 16.6 Labeled N (^{15}N) recovered in alley-cropped maize and trees supplied with biomass of *ex-situ* grown trees that had been treated with ^{15}N in the subhumid highlands of Kenya

	Labeled N in plants (kg ha^{-1})					Recovery of labeled N (%) at maize harvest							
	Maize					Maize							
Trt-	Grain	Cob	Stover	Roots	Tree leaves	Grain	Cob	Stover	Roots	Total	Tree leaves	Soil	Unaccounted?
Call	24.0 b	1.4 a	17.3 b	3.3 b	8.2 a	5.3 a	0.3 a	2.9 b	0.8 b	9.3 b	2.7 b	69.3 a	19.6 b
Leuc	32.7 a	1.8 a	21.8 a	4.7 a	6.4 a	6.5 a	0.3 a	5.0 a	1.4 a	13.0 a	2.1 a	55.0 b	29.7 a

Means followed by the same letter within a column are not significantly different at $p < 0.05$. Trt- = treatments with enriched ^{15}N calliandra (call) and leucaena (leuc) prunings
Source: Mugendi et al. (2000)

and decomposition of *Erythrina poeppigiana* root nodules. Babbar and Zack (1994, 1995) concluded from studies in non-shaded and shaded (with *E. poeppigiana*) coffee plantations that although the amount of mineralized N present was higher in shaded- than in non-shaded plantations, less N was leached from the shaded plantations, indicating that N cycling was more efficient in shaded- than in non-shaded plantations.

Table 16.7 Biomass production, turnover and recycling index for four shaded perennial-crop systems in Costa Rica[a]

Component	Shade production system			
	Erythrina + coffee	*Cordia* + coffee	*Erythrina* + coffee	*Cordia* + coffee
Fine root biomass, Mg ha^{-1}	2.6	4.5	3.8	7.0
Standing biomass, Mg ha^{-1}	35.4	37.1	44.5	63.7
Turnover, Mg ha^{-1}	20.0	5.7	22.9	11.4
Recycling, %	56.4	15.3	51.4	17.9
N in standing biomass, kg ha^{-1}	522	286	357	400
N turnover, kg ha^{-1}	461	114	447	169
N recycling, %	88.3	40.0	125	42.3
P in standing biomass, kg ha^{-1}	46.0	34.0	38.0	50.0
P turnover, kg ha^{-1}	35.0	7.0	40.0	24.0
P recycling, %	76.1	21.5	105	48.0
K in standing biomass, kg ha^{-1}	338	229	428	346
K turnover, kg ha^{-1}	260	54.0	177	73.0
K recycling, %	77.0	23.5	41.3	21.1

[a]Calculated from Fassbender (1993)
Source: Nair et al. (1995)

16.5 Soil Fertility Improvement through Trees in Agroforestry Systems

16.5.1 Tree Biomass and Its Decomposition

On average, the rate of biomass production of evergreen rainforest is estimated to be 20,000 kg ha^{-1} yr^{-1}. In the semi-deciduous forest, the typical rate is also about 20,000 kg ha^{-1} yr^{-1}, while in the high-altitude forest the rate is slightly lower. In savanna communities, the typical rate varies from 10,000 kg ha^{-1} yr^{-1} for moist savanna to 5,000 kg ha^{-1} yr^{-1} for dry savanna. In desert scrub areas the rate is 2,500 kg ha^{-1} yr^{-1} or less (Young 1989). The leaf biomass production rates of various multipurpose trees, grown in agroforestry systems or as plantations, are given in Table 16.3. The alley-cropping data in the table only refer to the tree component of these systems. In the IITA study, from which the Nigerian data were drawn, the tree rows were 4 m apart, and thus occupy about 25% of the total ground area; the project site lies on the margin between the moist subhumid and humid zones, where the expected net primary productivity is 20,000 kg ha^{-1} yr^{-1} (Young 1989). The typical annual rate of leaf biomass production of multipurpose trees in alley cropping in this zone is between 2,000 and 4,000 kg dry matter or 8 to 16 t fresh matter. Thus, the biomass production from the tree component in AFS can approach that in natural ecosystems in the same climatic zone, and may even exceed it if improved species and good management practices are used.

Trees in managed land-use systems frequently cause favorable changes in soil physico-chemical properties through organic matter inputs (mainly litter and fine root dynamics) into the system (Sections 16.2, 16.3, and 16.5.2). When evaluating the contribution of tree biomass production toward maintaining soil organic content, it is, however, essential to establish which of the four plant components of this biomass C: leaf (herbaceous), reproductive (fruit and flower), wood, and root C will be harvested and which will be returned to the soil. This will depend on several factors, especially the management levels and practices as well as the specific tree species and the environmental conditions. For example, if a fast-growing tree/shrub is grown and harvested as a fuelwood species rather than as a mulch producer, the amount of biomass as mulch added to the soil and its contribution to soil organic matter will, naturally, be less.

A substantial body of research data became available on the quantity and nutrient content of biomass produced by different trees and shrubs in AFS, primarily from tropical alley cropping and improved fallow systems in Sub-Saharan Africa during the 1990s under a variety of conditions (Chapter 6). Most reports deal with N; other elements such as P and K are less common. The C:N ratios of leaf biomass of 17 N_2 fixers included in Table 16.2 range from 10 to 25, whereas for non-N_2 fixers, the range is from 14 to 32. With an assumed 45 to 50% of C content for leaf biomass, these numbers indicate the leaf N content in the range of 2 to 5% for N_2 fixers and 1.4 to 3.5% for non-N_2 fixers. Considerable variations exist in the reported values of P and K contents (0.15 to 0.29% for P and 0.9 to 1.52% for K) in the leaf biomass of common agroforestry tree species (Nair 1993; Palm 1995; Kumar et al. 1998). The quantities of biomass produced by different trees under various conditions also differ substantially (Table 16.3). Thus, the extent of soil fertility improvement via nutrient cycling resulting from tree biomass decomposition in AFS is extremely site-specific.

Although trees in AFS can supply N to associated crops following litter decomposition, their ability to provide nutrients other than N is rather limited. The situation of inherently low P status of many tropical soils is made worse by their high P fixation rates caused by high levels of iron and aluminum (Buresh et al. 1997). Long-term cropping with low- or no external input of P further exacerbates the problem. The application of tree biomass to such highly weathered soils have resulted in increases in crop-available P (Jama et al. 1997), possibly due to P release from biomass decomposition but also indirectly due to the production of organic acids as byproducts of biomass decomposition which could help solubilize P and make it available for crop uptake.

Reviewing studies on the nitrogen content of litterfall and prunings, Young (1989) provided some data on various tree species in agroforestry systems in humid and moist subhumid climates. In alley-cropping systems, some species are capable of supplying 100–200 kg N ha^{-1} yr^{-1} if all the prunings are left on the soil; this is approximately the same as the amount of nitrogen that is removed during harvest in cereal/legume intercropping systems. In coffee and cacao plantations with shade trees, many of which are N_2 fixing (see Table 8.1), the return from litter and prunings is 100–300 kg N ha^{-1} yr^{-1}, which is much higher than the amount removed during harvest or derived from nitrogen fixation. Table 16.8, based on reports of Young (1989, 1997), shows general estimates of the amounts of biomass (both aboveground and belowground) that will need to be added to the soil to maintain soil organic matter in the three major climatic zones of the tropics.

Microsite enrichment by certain trees is a soil-fertility-related process that has been reported by several investigators in different countries and regions. In a study involving some of the common savanna tree and shrub species growing in highly weathered and infertile Ultisols of the Mountain Pine Ridge savannas of Belize (17°N

Table 16.8 Plant biomass amounts required to maintain soil organic carbon content in different climatic zones of the tropics

Climatic zone	Initial topsoil carbon	Topsoil carbon	Oxidation loss	Erosion loss	Required addition to soil humus	Required plant residues added to soil	
						Above-ground	Roots
	(kg C ha^{-1})	(%)	(kg C ha^{-1} yr^{-1})				
Humid	30,000	2.0	1,200	400	1,600	8,400	5,800
Suhumid	15,000	1.0	600	200	800	4,200	2,900
Semiarid	7,500	0.5	300	100	400	2,100	1,400

Source: Young (1989, 1997)

latitude, 89°W longitude), Kellman (1979) reported that trees enriched the soil below them in terms of Ca, Mg, K, Na, P and N. In some cases, the levels of these nutrients approached or exceeded those found in the nearby rainforest. The author concluded that the gradual accumulation of mineral nutrients by perennial, slow-growing trees, and the incorporation of these into an enlarged plant-litter-soil nutrient cycle was the mechanism responsible for the soil enrichment. Similar results of increased nutrient-content of soils under *Prosopis* spp. (locally known as the *khejri* tree: Chapter 9, Section 9.4.3) growing in an arid environment in India, a well-cited example of arid-zone agroforestry, has been reported (Mann and Saxena 1980). Vandenbeldt (1992) has also reported similar results under scattered *Faidherbia* (syn. *Acacia) albida* trees in West Africa. Rhoades (1997) summarized the reported results of some such studies on the influence of parkland trees (for a description of parklands, see Chapter 9, Section 9.4.1) on soil and crops (Table 16.9). There may be several other nutrient-enhancing species that already play a significant role in many traditional farming systems, but their potentials have scarcely, if at all, been scientifically studied and quantified.

16.5.2 Tree Roots

Roots are a component of primary productivity, although they are seldom considered in conventional plant productivity calculations. While the roots of annuals function on a seasonal basis, tree roots function all year round. Roots of woody perennials change their environment by accumulating dead root litter and redistributing nutrients. In competitive environments, survival

Table 16.9 Influence of parkland trees on soil and crops

Soil description/source	Tree species	Condition	Total C	Total N	Ca	Mg	K	pH	Crop response[a]
			%		cmol kg^{-1}				
North-central Senegal (Dancette and Poulain 1969) Soil depth 0–20 cm	*Faidherbia albida*	Canopy Open	3.70 2.70	0.40 0.30	1.61 1.13	0.71 0.62	0.10 0.07	5.7 5.5	Groundnuts: +37% Sorghum: +200%
Central Plateau, Burkina Faso (Depommier et al. 1992) Soil depth 0–20 cm	*Faidherbia albida*	Canopy Open	0.90 0.78	0.13 0.90	5.80 5.05	2.08 2.00	0.65 0.38	6.7 6.6	Sorghum grain: +115%
Lakeshore Plain, Malawi (Rhoades 1995; Sake et al. 1994) Soil depth 0–15 cm	*Faidherbia albida*	Canopy Open	2.50 2.20	0.22 0.19	5.71 6.84	1.50 1.78	0.98 0.87	6.3 6.3	Maize grain: +100 – 400%
South-central Mexico (Farrell 1990) Soil depth 0–15 cm	*Prunus capuli* *Juniperus deppeana*	Canopy Prunus Juniperus Open	1.34 0.63 0.45	0.09 0.04 0.03	6.50 6.60 3.45	1.29 1.24 0.62	0.58 0.84 0.33	6.6 7.4 6.2	Maize grain Prunus: −50% Juniperus: −50%
South Eastern Mali (Kater et al. 1992) Soil depth 0–20 cm	*Vitellaria paradoxa* (VP) *Parkia biglobosa* (PB)	Canopy Open	0.66 0.51	0.06 0.05	1.68 1.45	0.67 0.42	0.27 0.16	6.0 6.0	Cotton: VP −2%; PB −66%; Sorghum: VP −44%; PB −65% Millet: VP & PB −60%

[a]Yield difference under tree canopy and open sites
Source: Rhoades (1997)

is the goal, and this will have a bearing on how much root is necessary for a given tree.

The root biomass of trees is usually 20–30% of the total plant biomass, but it may be as low as 15% in some rain forests or as high as 50% or more in semiarid and arid climates. This biomass consists of structural roots (medium to large in diameter and relatively permanent), fine roots (less than 2 mm diameter), and associated mycorrhizae. Root abundance is usually expressed in terms of the so-called root length density expressed as the length of roots per unit area of soil surface (cm root cm^{-2} of soil surface) or per unit volume (cm root cm^{-3} of soil volume) (Bowen 1985). In general, rooting densities of trees are lower than those of cereals and herbaceous legumes. Of course, the rooting density and distribution of a plant depend on various site-related factors apart from the genetic factors associated with plant species. Combining trees and crops increases rooting densities and reduces inter-root distances, which increases the likelihood of inter-plant competition (Young 1989).

- The common methods for studying root systems under field conditions are the so-called invasive methods that help describe root system architecture and distribution as an indication of the volume of soil explored (Smit et al. 2000; Bayala et al. 2019). These include:
- Core soil sampling (monoliths): Roots from soil cores are washed free of soil using sieves or automated root washers; from the roots so extracted, root characteristics are such as weight, length, root length density, etc. are estimated manually or using software-driven scanning equipment
- Trenching to get a wall profile for root distribution studies (e.g., logarithmic spiral trench method: Tomlinson et al. 1998)
- Excavation around an individual tree to specified depth and horizontal distance to observe root architecture
- Rhizotron technology, which allows direct observations of the fine root dynamics.

All these methods have some limitations and drawbacks, but they can provide a range of information on root distribution and interactions with companion plants, but not nutrient uptake functions. More sophisticated "non-invasive" methods such as MRI (magnetic resonance imaging), Gamma-ray NMR (nuclear magnetic resonance), isotope labeling, modeling (e.g., the correlation between root weight and some of the more easily measurable aboveground growth variables), and others have been developed; but, they are not yet widely used in agroforestry research.

One of the main difficulties in assessing the root biomass of trees by the available (conventional invasive) methods is that the annual net primary production of roots is substantially more than the standing biomass found at any one time. This is mainly because fine roots are continuously sloughed off, and new ones are produced in their place. Fine roots are short-lived, non-woody, and tiny organs that account for about 27 to 75% of the annual net primary productivity of forests (McCormack et al. 2015). They are in a state of dynamic equilibrium or constant flux. As mentioned, they are constantly produced and they decompose continuously, and in that process, release substantial quantities of carbon and nutrients, especially in natural ecosystems (Finér et al. 2011; Xiong et al. 2018). In some respects, then, the build-up and regeneration of the root system are similar to that of the aboveground biomass: the structural roots are comparable to the trunk and branches as they have a steady growth increment and slow turnover, whereas the feeder (fine) roots – like the leaves, fruits, and flowers – are subject to shedding and regrowth.

It is now well-known that fine roots constitute a remarkable sink for carbon and nutrients and play a crucial role in driving annual net primary production, nutrient cycling, and carbon allocation (Jackson et al. 1996a, b; Green et al. 2005; Maeght et al. 2015a, b). In fact, "the small diameter, relatively short lifespan, and low C:N ratio of fine roots result in their rapid turnover and quick decomposition compared to woody biomass" (Jackson et al. 1996a, b). A close correlation between fine roots and foliage in terms of biomass and area has been reported for several forest trees (O'Grady et al. 2006; Jia et al. 2015), implying a tight coupling between production and absorption. Many authors (Finér et al. 2011; Montagnoli et al. 2019) also reported that fine root production is a function of environmental variables and it is high when conditions are generally conducive for growth (e.g., soil water status: Lima et al. 2010). Likewise, aboveground litterfall and belowground root turnover both increase soil organic matter. Root turnover and the effect of this process on soil organic matter is a critical factor in the evaluation of agroforestry systems.

The contribution of roots to soil organic matter has, unfortunately, not received serious attention. The ability of the root system to improve soil organic matter even where all above-ground biomass is removed, as discussed earlier, is a crucial factor in low-input agricultural systems with low productivity levels. Some data on fine root biomass in managed and natural ecosystems in the humid and semiarid tropics were compiled by Szott et al. (1991b). Ewel et al. (1982), who compared root biomass with leaf biomass (not total aboveground biomass) for a range of land-use systems in Costa Rica, found that the total root biomass in agroforestry systems (cacao + *Cordea alliodora*, and coffee + *Erythrina*) was substantially higher than in sole crops of maize or sweet potato, and *Gmelina* plantation at the same site. Mycorrhizal associations, that is, symbiotic associations between roots and soil fungi, are also important in soil-plant relationships (see also Section 17.6.2). Mycorrhizae absorb carbohydrates from the host plant, and, in turn, function as an extended root system, which increases nutrient absorption (e.g., P). When trees are introduced to a site for the first time, mycorrhizal inoculation, like *Rhizobium* inoculation, might be beneficial. In summary, the important role of roots in improving soil organic matter content in general and its special significance in multi-species plant associations such as agroforestry systems have been recognized for a long time; however, research in this vital area is still lacking; there is a clear need for further studies on this topic.

16.5.3 Deep Capture of Nutrients

Plant-available nutrients can be found in soil layers that are not easily accessed by annual crops because their root systems are either shallow (limited often to top 30 cm of soil surface) and/or have restricted lateral spread. Plant available nutrients (such as NO_3^-, SO_4^{2-}, K^+, Ca^{2+}, and Mg^{2+}) can be transported to deeper soil layers through downward leaching when the amount of available nutrients (supply) exceeds plants' demand for that nutrient. Increased biological breakdown of SOM, excessive input of fertilizers and other nutrient-rich materials, high rainfall or excessive irrigation, or poor plant growth can lead to nutrient accumulation in soils and enhance the chances of their leaching. Biological breakdown of SOM in deeper soil layers can also lead to the release of NO_3^-, SO_4^{2-}, and phosphates, whereas chemical breakdown of soil minerals in deep soil layers could release Ca^{2-}, Mg $^{2+}$. The ability of perennial plants such as trees and shrubs used in AFS to acquire and retrieve such nutrients that annuals cannot access could potentially increase nutrient use efficiency and therefore biological productivity, as well as help reduce the transport of such mobile nutrients to groundwater resources and create environmental hazards.

Roots of perennials can undoubtedly extend beyond the rooting depth of annual crops and it has long been recognized that in some species, roots extend far deeper into the soil than the rooting depth of common crops (Stone and Kalisz 1991). Following this realization, some investigations have been conducted on the deep-rooting attribute of some agroforestry trees to understand the spatial distribution and temporal patterns of their root growth (Jonsson et al. 1988; Ruhigwa et al. 1992; van Noordwijk et al. 1996). Based on such information, the concept of Deep Capture of Nutrients has been proposed to refer to nutrient uptake by tree roots from deeper soil layers (Mekonnen et al. 1997; Buresh and Tian 1997). One of the widely quoted studies on this aspect is from western Kenya in the 1990s. On farmers' fields (acid soils, Kandiudalf), Mekonnen et al. (1997) noted the accumulation of fairly large quantities of nitrate (70 to 315 kg N ha^{-1}) at 0.5 to 2.0 m depth under unfertilized maize and attributed it to the formation of nitrate by mineralization of SOM and the sorption and retention by clay minerals. Fast-growing trees such as *C. calothyrsus*, *Sesbania sesban*, and *Eucalyptus grandis* that were grown in rotation with maize rapidly put out their roots into this nitrate-accumulation zone and took up the sorbed nitrate that had not been taken up by maize roots possibly because maize roots did not go that far down (Hartemink et al. 1996; Jama et al. 1998). Jama et al. (1997) also showed that fast-growing trees with high root length densities could rapidly utilize subsoil nitrate on soils with no chemical or physical barriers to rooting. *S. sesban* and *C. calothyrsus* had root-length densities of >1.0 cm m^{-3} to below 1.5 m depth and they reduced soil nitrate throughout the 2-m deep soil profile (Figure 16.9). The reduction in soil nitrate (150 to 200 kg N ha^{-1}) in the top 2 m corresponded to a large accumulation of N (>300 kg N ha^{-1}) in the aboveground biomass of both *S. sesban* and *C. calothyrsus*. Slower-growing *Grevillea robusta* only accumulated 107 kg N ha^{-1} in the aboveground biomass, and soil nitrate increased rather than decreased during the 11 months after establishment (Figure 16.10).

The concept of deep capture of nutrients was proposed based on the possibility that tree roots may take up nutrients from deeper layers of soil below the nutrient-absorbing zone of agricultural crops (> about 30 cm deep from the surface). The rationale is that the nutrients so absorbed by trees could eventually become available to crops grown in association with such trees following the decomposition of the fallen tree-litter. In addition to the term deep capture of nutrients, two other terms have been proposed to denote similar processes: Nutrient Pumping and Safety Net (see also Chapter 14, Section 14.3.2). Both terms are used with or without the prefix "biological," i.e., nutrient pumping or biological nutrient pumping, and safety net or biological safety net. Nutrient pumping refers to the tree-mediated transfer of nutrients from lower soil depths to surface layers,

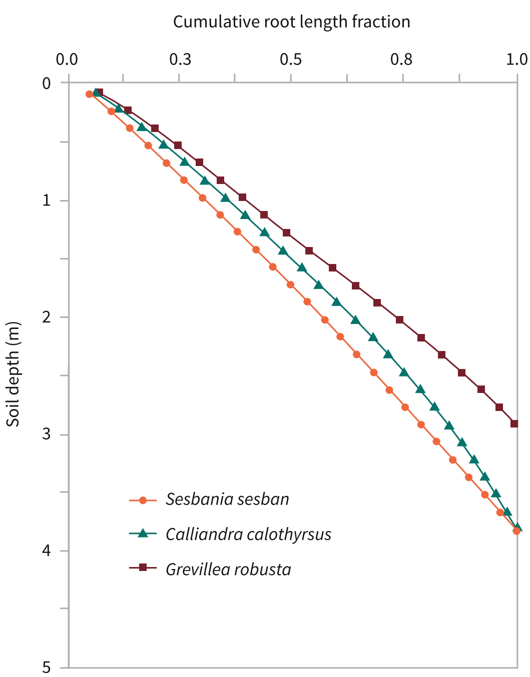


Figure 16.9 Cumulative root-length densities of three agroforestry tree species in western Kenya. Source: Jama et al. (1998)

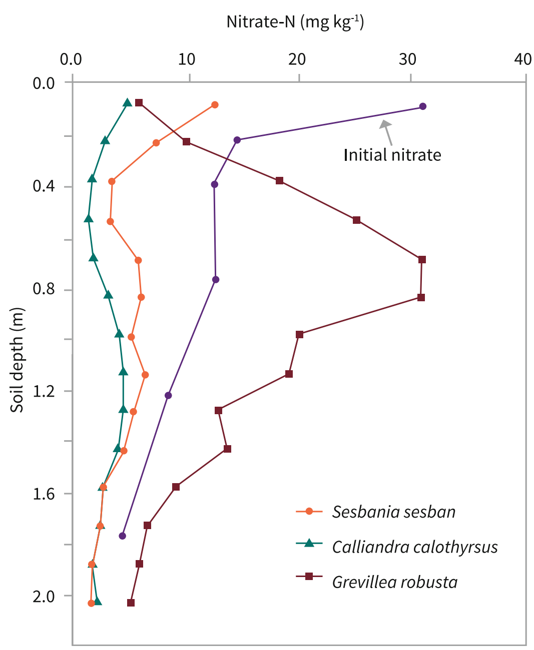


Figure 16.10 Effects of trees on soil nitrate eleven months after planting the seedlings in western Kenya. Source: Jama et al. (1998)

and the safety net implies that tree roots "intercept" nutrients that are leached from the surface layers and reduce the nutrient loss through leaching. The projection is that the combined effects of nutrient pumping and safety net, which is not different from the effect of deep capture, may enhance nutrient availability to crops and improve overall nutrient use efficiency.

It has been known for a long time that nutrient uptake from subsoil could be higher in tree crops in seasonally dry tropical climates when the surface soil dried out. Breman and Kessler (1995) reported, however, that nutrient pumping by trees in West African savannas was of limited importance because many soils were either too shallow or dry and nutrient-poor at depth to make nutrient pumping a useful strategy, and most trees present in the landscape were too shallow-rooted (while some were very deep-rooted). The earlier cited study of Jama et al. (1998) in western Kenya showed that planted fallows of fast-growing trees (*C. calothyrsus*, *S. sesban*) recycled considerable amounts of subsoil nutrients, which could be made available to subsequent crops through application of the tree biomass, either directly or after use as animal fodder. However, where tree spacing is wide, as in many agroforestry associations, tree root growth in the subsoil may be limited to areas close to the trees. In certain cases, nearness of trees to one another in dense stands may determine the belowground architecture (deeper and more compact root systems) and hence the magnitude of subsoil-nutrient recovery (Kumar and Jose 2018), implying that stand density management (thinning and initial population control) is a critical factor that influences deep-capture of subsoil nutrients.

Buresh et al. (2004) suggested that the roots of perennials can act as a safety net in agroecosystems such as agroforestry systems involving combinations of annuals intercropped under or between perennials. In such situations, the roots of the perennial species could be more effective than those of a young annual in capturing the mobile nutrients. As the growth and nutrient demand of the annual species accelerate, there could be competition between the annual and perennial species in the upper soil layers where the annual roots concentrate. But a dense and active root system of the perennial species below this zone creates a safety net and minimizes competition with the annual species in this zone and but also reduces leaching loss beyond this layer.

The retrieval of nutrients by the perennial species from below the root zone of annuals, however, has not been quantified rigorously. Radioactive tracers (such as ^{32}P and ^{35}S) and stable isotopes such as ^{15}N) have been used for monitoring such phenomena (Buresh et al. 2004), but mostly as sporadic and isolated experiments rather than coordinated and long-term projects. The potential for increased capture of nutrients from deep soil and recycling them for increased nutrient use efficiency in agroforestry systems with shallow-rooted annuals and deep-rooted perennials is credible but has not attracted deserving research attention, and therefore their actual benefits have not yet been convincingly demonstrated or quantified at the field level.

16.6 Concluding Remarks

Agroforestry systems can improve overall soil productivity in various ways, especially under the low-input, resource-poor farming conditions in the tropics and subtropics. The important ones are related to the maintenance (and improvement) of soil organic matter status and efficient nutrient cycling. Several opportunities exist for modifying nutrient cycling through management, which results in more efficient use of soil nutrients, whether added externally (such as fertilizers) or made available through natural processes (e.g., weathering) when compared to agricultural systems. The underlying mechanisms that contribute to efficient nutrient cycling, as well as other nutrient cycling considerations in agroforestry systems, are summarized below:

1. There is potential for enhanced uptake of nutrients from deeper soil horizons (where they might be available as a result of rock weathering or percolation past herbaceous plant roots). The deep root systems of trees

may reach these sites, which are often beyond the reach of the roots of common agricultural crops. The magnitude of this process, which is sometimes called – maybe erroneously – nutrient pumping, is not known; it might be a significant factor of soil fertility improvement in AFS.

2. Gains from symbiotic N_2-fixation by trees (Chapter 17) can be enhanced through tree-species selection and admixture. It is important, however, to distinguish between nitrogen fixation (input into the plant-soil system), and nitrogen addition through litter or prunings (which may result in an internal transfer within the system). Much of the nitrogen in the litter is taken up from the soil, originating either from stored reserves in the soil or from added fertilizers. Detailed investigations are needed to determine how much nitrogen that is fixed by the tree component in AFS becomes available to the herbaceous component during its current and subsequent seasons. These issues are considered in more detail in the following chapter (Chapter 17).
3. Nutrient release from tree biomass can be synchronized with crop requirements by regulating the quality, quantity, timing, and method of application of tree prunings as manure or mulch, especially in tropical alley cropping. Different shrubs used in alley-cropping systems vary in the quantity, quality, and decomposition dynamics of leaf biomass. The timing of hedge pruning in alley cropping (and therefore, application of leaf biomass as a source of manure to the planted crop) can be regulated in such a way that the nutrient (especially N) release through the decomposition of biomass is synchronized with the peak period of the crop's nutrient demand.
4. Management practices that lead to improved organic matter status of the soil will lead inevitably to improved nutrient cycling and better soil productivity. Although the principal recognized benefit from tree biomass in AFS is nutrient-related, organic-matter addition to the soil has several other advantages too.

A question that is commonly asked in the context of agroforestry and soil fertility management is, to what extent can agroforestry systems contribute to soil organic matter maintenance and accumulation? This chapter contains estimates and their underlying premises of the amounts of biomass (both aboveground and belowground) that will need to be added to the soil to maintain soil organic matter in the three major climatic zones of the tropics. The validity of these assumptions is debatable, but the model gives a framework for calculating the amounts of organic residues that need to be added, which, in this case, attains a level of 8,000 kg above-ground dry matter per ha per year for humid tropical regions. Corresponding values for the subhumid and semi-arid zones are 4,000 and 2,000 kg ha^{-1} yr^{-1} (dry matter) respectively. The values indicate that the levels of plant biomass additions mentioned above can be met if all of the total tree biomass is added to the soil, which is hardly ever the case (these additions are dependent upon the land user's objectives and motivations). Trees, however, are not the only sources of the addition of organic matter or plant biomass to the soil in an agroforestry system; herbaceous components may also constitute a significant addition (e.g., cereal straws).

The message that emanates from this chapter is that management practices are the key to organic matter maintenance: returning as much of the tree- and crop residues as possible to the soil is a big step forward under tropical agroforestry conditions. Transporting plant residues from outside the farm or other parts of the farm may be an option, but the availability of large quantities of bulky organic materials and labor and cost considerations could be important deterrents.

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17 Biological Nitrogen Fixation and Nitrogen Fixing Trees

Contents

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Abstract

Biological nitrogen fixation (BNF) refers to the process by which the nitrogen that is present abundantly in the atmosphere as non-reactive molecular dinitrogen (N_2) is converted into reactive forms that become available to plants and thereby to all life forms. The key process of BNF is the conversion of N_2 to ammonia (NH_3) catalyzed by the enzyme *nitrogenase*, which occurs in a group of microorganisms that exist in symbiotic association with certain plants especially legumes, or as free-living organisms. *Frankia*, a genus of actinomycetes, also can form a symbiotic association with about 25 genera of non-leguminous plants. Next to photosynthesis, BNF is the second most important biochemical reaction that supports life on Earth. Being a subject of enormous importance and long history, voluminous information is available on different aspects of BNF. This chapter provides an overview of the key principles of BNF and explores its role in agroforestry with special reference to N_2-fixing trees (NFTs) that are found mostly in the tropics and subtropics. The major topics included are an explanation of the process of dinitrogen fixation, rhizobia and root nodulation, short accounts of the nitrogen-fixing (legumes and actinorhyzal) plants, measurement of symbiotic nitrogen fixation, transfer of fixed nitrogen and factors affecting it, and the management of BNF in agroforestry. During the early days of agroforestry research in the 1980s, some efforts were initiated for capturing the benefits of BNF, including field-level evaluation of NFT cultivars and provenances and estimation of their nitrogen-fixing potential. The efforts, however, were not pursued vigorously such that the results reported, although used repeatedly, are of limited value, and even questionable at times. The NFTs constitute a valuable natural resource, which when managed properly, can be used in perpetuity in AFS for enhancing plant productivity.

17.1 Introduction

Biological nitrogen fixation (BNF) is the second most important biochemical reaction next to photosynthesis that supports life on Earth. It refers to the process by which the nitrogen that is present abundantly in the atmosphere as non-reactive molecular dinitrogen (N_2) is converted into reactive forms (sometimes referred to as N_r) that become available to plants and thereby all forms of life. The key process of BNF involves the conversion of N_2 to ammonia (NH_3). This reaction is catalyzed by the enzyme *nitrogenase* present in a group of microorganisms that exist in symbiotic association with certain plants especially legumes or as free-living organisms. The most important nitrogen-fixing organisms are bacteria of the genus *Rhizobium* and some other genera collectively called the rhizobia or the rhizobial group, which inhabit the roots of most legumes. *Frankia*, a genus under the phylum Actinobacteria (order: Actinomycetales) also can form symbiotic association with some (about 25) genera of non-leguminous trees.

Nitrogen (N) is the kingpin of plant production. Although it is the most abundant element (approximately 78% of the air) in the Earth's atmosphere, paradoxically, its deficiency is the major factor that limits food production, especially in the tropics. The process of BNF has been the principal way of converting the inert molecular N_2 in the atmosphere to reactive N (NH_3), until the development of the Haber-Bosch process for producing commercial nitrogen fertilizers in the early 1900s. Today BNF and N fertilizers produce almost equal amounts of N globally, BNF ranking slightly higher. Fertilizer (chemical) sources of nitrogen that are dependent on non-renewable fossil fuels may have harmful effects on the environment and may impact food quality; moreover, fertilizers are beyond the economic reach of many smallholder farmers in developing countries. The exploitation of the time-tested BNF, on the other hand, offers an economically and environmentally sound approach to meeting crop demands as the main or supplementary source of N. Given that many of the tree legumes used in agroforestry have BNF capabilities through symbiotic association with *Rhizobia* and other N_2-fixing microorganisms, BNF is an extremely important topic in agroforestry. Indeed, as explained in Chapters 1 and 13, one of the motivations for initiating the "agroforestry movement" as well as the expectations from agroforestry, center around making the best use of nature's gift of BNF.

Being a subject of enormous importance and long history, voluminous information is available on the different aspects of BNF. Without going into the details especially of topics that are outside the scope of this book, this chapter will at first present some of the key background principles of BNF and then focus on explaining and exploring the role of BNF in agroforestry with special reference to N_2-fixing trees (NFTs).

17.2 Dinitrogen Fixation

The two atoms of N_2 (molecular nitrogen in the atmosphere) are held together by a strong triple bond (N≡N). Most legume species can form a mutualistic relationship with the soil-inhabiting root nodule bacteria (*Rhizobia:* see Section 17.3) that use solar energy captured by the plant in photosynthesis to break up the triple bond and form the reactive N species (Figure 17.1). The reaction is:

$$N \equiv N + 8\,H^+ + 8\,e^- \rightarrow 2\,NH_3 + H_2$$

Ammonia (NH_3) that is the direct product of the reaction is rapidly ionized to the ammonium ions (NH_4^+).

The BNF is an energy-expensive process and consumes 16 to 24 moles of ATP (Adenosine

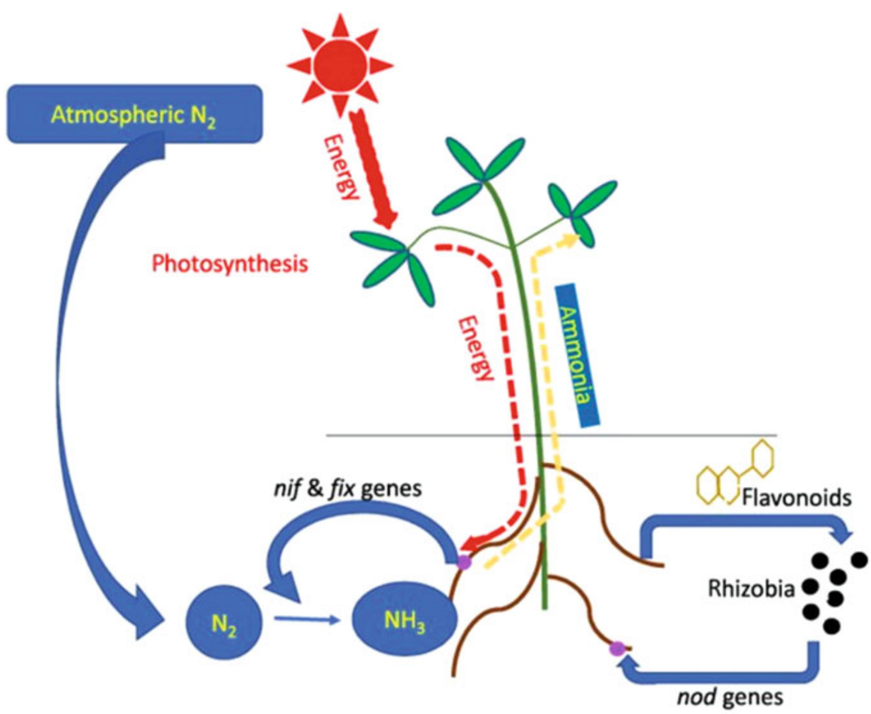

Figure 17.1 A summarized model for symbiotic nitrogen fixation in legumes by rhizobia. Adapted from Lindström and Mousavi (2020). Reproduced with permission

triphosphate) for the reduction of one mole of N_2 with the release of ADP (Adenosine diphosphate), inorganic phosphate and hydrogen gas as presented in the following equation.

$$N_2 + 8H + +8e^- + 16\ ATP = 2NH_3 + H_2 + 16ADP + 16\ Pi$$

As the equation shows, two moles of ammonia are produced from one mole of nitrogen gas. Delivery of eight electrons and eight protons results in the catalyzed reduction of one N_2 molecule to two ammonia molecules, releasing one H_2 molecule. The reaction requires 16 ATP molecules. Additionally, 12 ATP molecules are consumed in nodule development. The resultant ammonia diffuses into the *cytosol* (the intracellular fluid of the cells) of the infected host cells, from where it is quickly assimilated. What follows is the synthesis and export of amino acids and/or ureides from the legume nodules to the host tissues.

17.3 *Rhizobia* and the Root-Nodule

17.3.1 *Rhizobia*

As mentioned, all bacterial genera and species known to inhabit the legume root (and occasionally stem) nodule tissues and reduce N_2 gas to ammonia are collectively known as "Rhizobia." The symbiotic N_2-fixing soil microorganisms such as rhizobia and *Frankia* are also called microsymbionts and their hosts, macrosymbionts. Until the early 1980s, all symbiotic N_2-fixing bacteria from leguminous plants were grouped under a single genus *Rhizobium*, with six species: *R. leguminosarum*, *R. meliloti*, *R. trifolii*, *R. phaseoli*, *R. lupini,* and *R. japonicum*. This taxonomy changed when Jordan (1984) and others used several phenotypic characteristics to identify and differentiate bacteria capable of nodulating legumes. Many novel records of nodulating bacteria, comprehensive studies of nodule structure, and an enormous increase in the number of genera and species of rhizobia have been reported during the past two decades (since 2000). The DNA-based methods (e.g., phylogenetic analyses of sequences of the 16S ribosomal RNA gene) have been increasingly used to characterize rhizobia, which led to the revision of rhizobial taxonomy. Recent estimates indicate that the root and stem nodule bacteria of legumes consist of 238 species belonging to 18 genera (Shamseldin et al. 2017).

Rhizobia were also classified into fast-growing, acid-producing, and slow-growing, alkali-producing groups based on their regeneration time and pH changes in the yeast extract mannitol medium containing bromophenol blue (Vincent 1970). Jordan (1982) created a new genus of *Bradyrhizobium* for accommodating the slow-growing strains and retained the fast-growing ones under the broad group of *Rhizobium*. The family Rhizobiaceae was also subdivided into two large groups based on the host range size: (1) those bacteria with a broad host range, e.g., *Bradyrhizobium* (Bradyrhizobiaceae) able to associate with several hosts and (2) those with a narrow host-range, e.g., *Ensifer* and *Mesorhizobium*. By far, the largest rhizobial genus is *Bradyrhizobium*, which nodulates the widest range of legumes, as well as the non-legume *Parasponia* (Parker 2015). The rhizobium taxonomy has, thus, been continually evolving with an ever-increasing volume of literature. However, the symbiotic relationship between the nodule bacteria and host legume still "remains the same as ever for all practical purposes and does not affect field-oriented programs on nitrogen fixation" (Rao 2014).

17.3.2 The Root Nodule

Biological nitrogen fixation involves the formation of root nodules on legumes (and some non-legumes). Symbiotic nitrogen fixation (SNF) can occur once the rhizobia are established inside the cells of root nodules (Figure 17.2). The question as to how leguminous plants can spot symbiotic partners from an enormous array of divergent bacterial communities in the soil has fascinated many. For almost all legumes studied, the first step in nodulation processes is the

Figure 17.2. *Sesbania* root nodules
Source: https://www.inaturalist.org/observations/10999554. Reproduced with permission

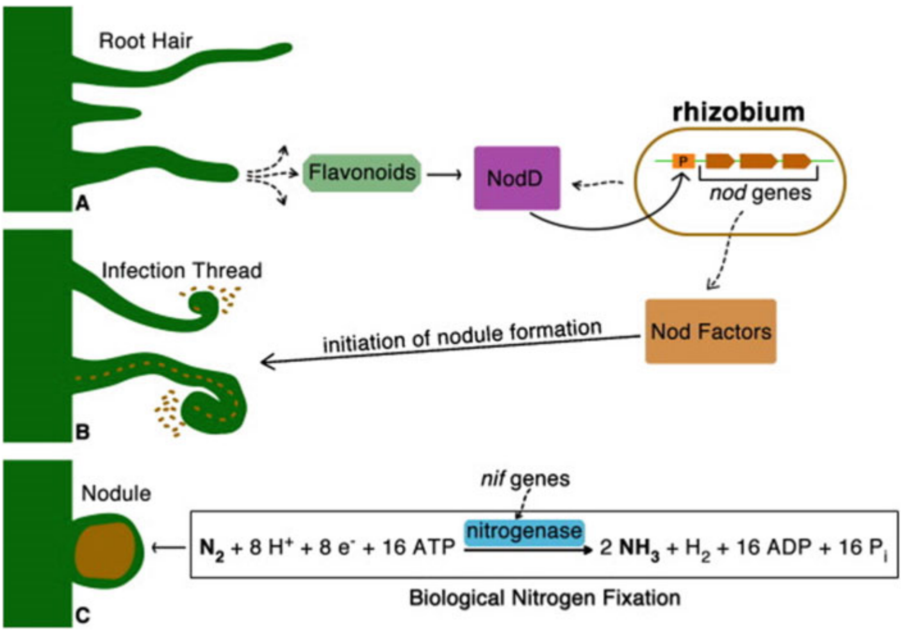

Figure 17.3. Schematic overview of the nodulation process and biological nitrogen fixation. Nodulation (**Nod**) **factors** are signaling molecules produced by bacteria (*Rhizobia*) during the initiation of nodules on the root of legumes. Adapted from Laranjo et al. (2014). Reproduced with permission from Elsevier

legume's production of a mix of compounds, mainly flavonoids (Figure 17.3), which induce the synthesis of a regulator, *Nodulation protein D* (*NodD*) in rhizobia (Wang et al. 2012; Downie 2014; Laranjo et al. 2014). Legumes generally "produce specific flavonoids that only induce *Nod* factor production in homologous (compatible) rhizobia," and therefore act as a crucial factor determining the host range (Liu and Murray 2016).

The invading bacteria grow and form infection foci from which infection threads are produced

(Figure 17.3), which then pass through the cell boundaries facilitating bacterial invasion into the cortex. Simultaneously, the cortical cells below the sites of infection begin to divide mitotically to develop the nodule primordium. The infection threads approach the developing primordia and the differentiated bacteria (called *bacteroids*) are released inside the nodule, where they multiply. The cytoplasm of a nitrogen-fixing symbiotic cell can host up to about 50,000 bacteroids. Several concurrent biological processes also operate within the mature nodules, which include reduction of N_2 in the bacteroids, carbon-nitrogen metabolism, and metabolite transport across cell membranes (Udvardi and Poole 2013; Clarke et al. 2014; Liu et al. 2018). More importantly, the host plant provides the microsymbiont with dicarboxylates (organic compounds containing two carboxylic acid groups) together with other nutrients in exchange for fixed nitrogen in the form of ammonium and amino acids (Udvardi and Day 1997).

The morphology and appearance of nodules vary considerably among the legumes. Nodules also differ in their size and number; most are small (usually less than 0.5 cm in diameter or length) but some can reach the size of a baseball. Herbaceous plants and trees with numerous nodules are generally characterized by smaller nodule sizes, which are less efficient in N_2 fixation. Effective nodules are large and are identifiable by their pink or reddish internal coloration owing to the presence of leghemoglobin, a nitrogen- and oxygen-carrying plant pigment. Young nodules are generally white or grey inside and are incapable of nitrogen fixation.

Legume nodules are also classified as determinate or indeterminate in growth (Sprent et al. 2013). While determinate nodules have a transient (short-lived) meristem, indeterminate nodules maintain meristematic tissues. Unlike in the annual and herbaceous legumes, nodulation in trees can be perennial and deep (Galiana et al. 2004). Many actinorhizal species (e.g., *Casuarina equisetifolia*), as well as woody legumes, bear perennial nodules. In some phreatophytic (a deep-rooted plant that is mostly or entirely dependent on water from a permanent ground supply) tree legume species such as *Prosopis juliflora*, deep nodulation has been reported (Felker and Clark 1982) that allows N_2 fixation even when the surface horizons of the soil are dry.

17.4 Nitrogen-Fixing Plants

17.4.1 The Family Leguminosae (Fabaceae)

Biological nitrogen fixation is a cardinal feature of the family Leguminosae or Fabaceae – the third largest family of angiosperms after Orchidaceae and Asteraceae, consisting of 19,300 species within 750 genera, and the second economically most important plant family, after Poaceae (Lewis et al. 2005). There are over 650 known NFT species, of which the vast majority (about 515) are legumes, i.e., members of the family Leguminosae. Almost all leguminous NFTs are tropical and subtropical species, a notable exception being *Robinia pseudoacacia*, the black locust tree that is endemic to a few small areas in the USA but has also been widely planted in other temperate regions as well. The voluminous literature that is available on various aspects of BNF deals almost exclusively with N_2 fixation by herbaceous crops. Nonetheless, as mentioned before, agroforestry offers a unique opportunity for exploiting the N_2-fixing qualities of woody perennials. The common N_2-fixing tree genera used in agroforestry systems are included in Tables 5.3 and 13.1, with their short profiles given in Chapter 13.

Legumes constitute the principal category of plants that form endosymbiotic interactions with rhizobia (Endosymbiosis is a phenomenon where bacteria occur in polyploid host cells as membrane-enclosed vesicles). The taxonomy of legumes is complex and has been rapidly evolving in the recent past, especially in the light of new molecular and morphological evidence including nodulation characteristics. Historically, legumes were treated as a single family (Leguminosae or Fabaceae), divided into three subfamilies: Papilionoideae, Mimosoideae, and Caesalpinioideae. After a comprehensive phylogenetic analysis, the Legume Phylogeny Working Group (LPWG 2017) has proposed a new classification scheme for Leguminosae consisting of six subfamilies. These changes may reflect a work in progress and may become widely accepted and used over time. Nevertheless, since they are not yet commonly used in agroforestry literature and may be confusing to the readers of this book, we will continue to use the familiar terms, i.e., the family Leguminosae or Fabaceae and its three subfamilies (Papilionoideae, Mimosoideae, and Caesalpinioideae).

Principal N_2-fixing Tree Legumes and Their Microsymbionts: Nitrogen-fixing leguminous trees and shrubs abound in tropical agroforestry (Table 17.1). Profiles of several of these species are provided in Chapter 13 (Annexure 13-I). Numerous such species also occur in the natural ecosystems of the world. Out of the nearly 160 NFT species/genera on which information on host-rhizobial associations is currently available (Andrews and Andrews 2017), around 50 are involved in agroforestry. The prominent trees and shrubs with agroforestry potential and their microsymbionts are listed in Table 17.1. It is believed that major legume tree species/genera are promiscuous; for example, *Leucaena leucocephala* forms associations with rhizobial genera *Ensifer*, *Mesorhizobium,* and *Rhizobium*; *Sesbania* spp. are nodulated with *Azorhizobium, Bradyrhizobium, Ensifer, Mesorhizobium, Neorhizobium*, and *Rhizobium*. *Faidherbia (Acacia) albida* is predominantly nodulated by *Bradyrhizobium,* but *Rhizobium* and *Ensifer* also are effective on it. Andrews and Andrews (2017) stated that "specific symbioses are likely to be at least in part related to the relative occurrence of the potential symbionts in soils of the different regions," underscoring the inherently promiscuous nature of many of these symbionts. Information on the host-rhizobial associations of many tree legumes is, however, lacking.

17.4.2 Actinorhizal Plants

While symbiotic N fixation is a "trademark" of the Family Leguminosae, there are many non-legumes, called actinorhizal plants, that develop an endosymbiotic association with the nitrogen-fixing soil actinomycete, *Frankia* (Family: Frankiaceae). In a manner analogous to rhizobial symbiosis, the host-*Frankia* association results in the formation of root nodules (Figure 17.4) and the provision of fixed nitrogen to the host plant in exchange for reduced carbon. Given its ecological significance, the topic of actinorhizal association has attracted considerable scientific attention in the recent past (Pawlowski and Newton 2008; Santi et al. 2013).

Actinorhizal plants form a large group of about 260 species (mostly woody shrubs and trees; Benson and Dawson 2007). They belong to eight dicotyledonous plant families of three orders: Fagales (Betulaceae, Casuarinaceae, and Myricaceae), Rosales (Rosaceae, Eleagnaceae and Rhamnaceae), and Cucurbitales (Datiscaceae and Coriariaceae) and are widely distributed from the cold regions of the earth (e.g., alder or *Alnus*) to the warm latitudes (e.g., *Casuarina*). The major species of actinorhizal plants in agroforestry belong to the genera *Alnus*, *Casuarina*, and *Allocasuarina* and, secondarily, to *Coriaria*.

More than 200 strains of *Frankia* have been isolated, although not all are of actinorhizal plant origin (Santi et al. 2013). *Frankia* can also subsist under free-living aerobic conditions (Pawlowski and Newton 2008), implying that symbiosis is usually facultative (i.e., optional, not obligatory) as in legumes. When suitable hosts are available, the microsymbionts enter the host plant roots either intracellularly through root hairs or intercellularly via crack invasion, depending on the host plant species (Pawlowski 2009). When *Frankia* hyphae enter a root hair, much like rhizobia, an infection-thread-like structure is produced, and a pre-nodule induced to form in the cortex. Simultaneously a nodule primordium is formed in the pericycle, and the infection thread grows transcellularly to reach the emerging nodule. *Frankia* induces the formation of multilobed,

Table 17.1 Legume-rhizobia symbioses (trees and shrubs) in the legume sub-families of recircumscribed Caesalpinioideae and Papilionoideae

Family, Tribe and Species	Endosymbiont
Recircumscribed Caesalpinioideae	
Ingeae	
Acacia auriculiformis	*Bradyrhizobium*
Acacia mangium	*Bradyrhizobium*,
	Ochrobactrum
	Rhizobium
Acacia mangium × *A. auriculiformis*	*Bradyrhizobium*
Acacia mearnsii	*Ensifer*
Acacia melanoxylon	*Bradyrhizobium*
Acacia saligna	*Bradyrhizobium*
	Ensifer
	Rhizobium
Acaciella angustissima	*Ensifer*
Calliandra calothyrsus	*Ensifer*
	Rhizobium
Calliandra grandiflora	*Ensifer*
	Mesorhizobium
	Rhizobium
Faidherbia albida	*Bradyrhizobium*
Inga edulis	*Bradyrhizobium*
Inga laurina	*Bradyrhizobium*
Mariosousa acatlensis	*Ensifer*
Senegalia laeta	*Ensifer*
Senegalia macilenta	*Ensifer*
Senegalia senegal	*Ensifer*
	Rhizobium
	Mesorhizobium
Mimoseae	
Anadenanthera peregrina	*Burkholderia*
Desmanthus illinoensis	*Rhizobium*
Desmanthus paspalaceus	*Mesorhizobium*
	Rhizobium
Desmanthus virgatus	*Rhizobium*
Leucaena leucocephala	*Ensifer*
	Mesorhizobium
	Rhizobium
Microlobius foetidus	*Bradyrhizobium*
	Rhizobium
Mimosa albida, *M. biuncifera*, *M.borealis*, *M. dysocarpa*, *M. polyantha*, *M. tricephala*, *Mimosa* sp.	*Ensifer*
	Rhizobium
Mimosa asperata	*Cupriavidus*
Mimosa benthamii, *M. goldmanii*, *M. monancistra*, *M. robusta*, *M. tequilana*	*Rhizobium*
Mimosa borealis, *M. lacerata*, *M. luisana*, *M. similis*	*Ensifer*
Mimosa ceratonia	*Rhizobium*
Mimosa cruenta, *M. magentea*, *M. ramulosa*, *M. reptans*, *M. schleidenii*	*Cupriavidus*
Mimosa diplotricha	*Burkholderia*
	Cupriavidus

(continued)

Table 17.1 (continued)

Family, Tribe and Species	Endosymbiont
	Rhizobium
Mimosa hamata, *M. himalayana*	*Ensifer*
Mimosa pigra	*Burkholderia*
	Cupriavidus
Mimosa polyantha	*Rhizobium*
Parapiptadenia pterosperma	*Burkholderia*
Parapiptadenia rigida	*Burkholderia*
	Cupriavidus
	Rhizobium
Piptadenia adiantoides, P. flava	*Rhizobium*
Piptadenia gonoacantha, *P. paniculata*	*Burkholderia*
	Rhizobium
Piptadenia stipulacea, *P. trisperma, P. vividiflora*	*Burkholderia*
Prosopis alba	*Bradyrhizobium*
	Ensifer
	Mesorhizobium
	Rhizobium
Prosopis chilensis	*Ensifer*
Prosopis cineraria	*Ensifer*
Prosopis farcta	*Ensifer*
	Mesorhizobium
Prosopis juliflora	*Ensifer*
	Rhizobium
Pseudopiptadenia contorta	*Burkholderia*
Stryphnodendron sp.	*Bradyrhizobium*
Vachellia abyssinica	*Mesorhizobium*
	Ensifer
Vachellia cochliacantha, *V. farnesiana*, *V. pennatula*	*Ensifer*
Vachellia gummifera	*Ensifer*
Vachellia horrida	*Ensifer*
Vachellia jacquemontii	*Ensifer*
Vachellia macracantha	*Ensifer*
	Rhizobium
Vachellia nubica	*Bradyrhizobium*
Vachellia seyal	*Rhizobium*
	Ensifer
Vachellia tortilis	*Ensifer*
	Mesorhizobium
	Rhizobium
Vachellia xanthophloea	*Mesorhizobium*
Xylia xylocarpa	*Bradyrhizobium*
Papilionoidieae	
Galegeae	
Clianthus puniceus	*Mesorhizobium*
Colutea arborescens	*Ensifer*
	Mesorhizobium
	Rhizobium
Sphaerophysa salsula	*Ensifer*

(continued)

Table 17.1 (continued)

Family, Tribe and Species	Endosymbiont
	Mesorhizobium
	Rhizobium
Halimodendron halodendron	*Rhizobium*
Genisteae	
Adenocarpus hispanicus	*Phyllobacterium*
Genista stenopetula	*Bradyrhizobium*
Retama monosperma	*Bradyrhizobium*
Retama raetam	*Bradyrhizobium*
Retama sphaerocarpa	*Bradyrhizobium*
	Phyllobacterium
Spartium junceum	*Bradyrhizobium*
	Phyllobacterium
Ulex europaeus	*Bradyrhizobium*
Hypocalypteae	
Hypocalyptus coluteoides, *H. oxalidifolius*, *H. sophoroides*	*Burkholderia*
Indigofereae	
Indigofera angustifolia	*Burkholderia*
Indigofera hirsuta, *I. senegalensis, I. tinctoria*	*Bradyrhizobium*
Indigofera filifolia	*Burkholderia*
Millettieae	
Millettia leucantha	*Bradyrhizobium*
Millettia pinnata (Syn: *Pongamia pinnata)*	*Rhizobium*
Tephrosia purpurea	*Bradyrhizobium*
	Ensifer
	Rhizobium
Podalyrieae	
Cyclopia buxifolia, *C. genistoides*, *C. glabra*, *C. intemedia*, *C. longifolia*, *C. maculata*, *C. meyeriana*, *C. pubescens*, *C. sessiflora*, *C. subternata*	*Burkholderia*
Podalyria burchelli, *P. sericea*	*Burkholderia*
Podalyria calyptrata	*Burkholderia*
Podalyria pinnata	*Burkholderia*
Virgilia divaricata	*Rhizobium*
Virgilia oroboides	*Burkholderia*
Robineae	
Gliricidia sepium	*Ensifer*
	Rhizobium
Robinia pseudocacia	*Mesorhizobium*
	Rhizobium
Sesbanieae	
Sesbania aculeata, *S. grandiflora*, *S. pachycarpa*, *Sesbania* sp.	*Ensifer*
Sesbania cannabina	*Ensifer*
	Neorhizobium
	Rhizobium
Sesbania exasperata	*Rhizobium*
Sesbania herbacea	*Rhizobium*
Sesbania punicea	*Azorhizobium*
	Mesorhizobium
	Rhizobium

(continued)

Table 17.1 (continued)

Family, Tribe and Species	Endosymbiont
Sesbania rostrata	*Azorhizobium*
	Bradyrhizobium
	Ensifer
	Rhizobium
Sesbania sericea	*Mesorhizobium*
	Rhizobium
Sesbania sesban	*Ensifer*
	Mesorhizobium
	Rhizobium
Sesbania virgata	*Azorhizobium*
	Rhizobium
Sophora alopecuroides	*Ensifer*
	Mesorhizobium
	Phyllobacterium
	Rhizobium
Sophora flavescens	*Bradyrhizobium*
	Ensifer
	Mesorhizobium
	Phyllobacterium
	Rhizobium
Sophora longicarinata, *S. microphylla*, *S. prostrata*, *S. tetraptera*	*Mesorhizobium*
Sophora viciifolia	*Mesorhizobium*
Thermopsideae	
Ammopiptanthus nanus, *A. mongolicus*	*Ensifer*
	Neorhizobium
	Pararhizobium
	Rhizobium
Anagyris latifolia	*Mesorhizobium*
Dalbergieae	
*Centrolobium paraense**	*Bradyrhizobium*
Dalbergia baroni, *D. louveli*, *D. madagascariensis*, *D. maritima*, *D. monticola*, *D. purpurascens*, *Dalbergia* sp.*	*Bradyrhizobium*
*Pterocarpus officinalis**	*Bradyrhizobium*
*Pterocarpus indicus**	*Bradyrhizobium*
Phaseoleae	
*Cajanus cajan**	*Bradyrhizobium*
Psoraleae	
Otholobium bracteolatum, *O. hirtum*, *O. virgatum*, *O. zeyhari*, *Otholobium* sp.*	*Mesorhizobium*
*Psoralea pinnata**	*Bradyrhizobium*
	Burkholderia
	Mesorhizobium

Details on trees and shrubs extracted from Andrews and Andrews (2017)
*All species have indeterminate nodules except the species marked with asterisk (*), which have both determinate as well as indeterminate nodules

Figure 17.4 A well-developed root nodule of an actinorhizal plant is composed of multiple lobes, giving it a coralloid appearance. It is also called "rhizothamnium". The example shown here is a nodule of *Ochetophila trinervis* (family Rhamnaceae). © 2002-2020 The Society for Actinomycetes Japan (Contributor: G. Vobis). Reproduced with permission

indeterminate nodules, which are modified adventitious secondary roots formed from the root pericycle (Figures 17.4, 17.5). Each lobe represents a modified lateral root and has an apical meristem (Lindström and Mousavi 2010).

Following infection, the nodule cells become full of branching *Frankia* hyphae surrounded by a perimicrobial membrane of host origin, forming special organalleles called *vesicles* (Figure 17.5). Nitrogen fixation occurs in these vesicles that usually develop after *Frankia* infection threads have invaded the nodule cells (Froussart et al. 2016). No vesicles are found in *Casuarina* or *Allocasuarina*, however. Dinitrogenase activity in such cases is localized in the hyphae, particularly in the intracellular non-septate hyphae, as in *Casuarina*, which serve as the symbiotic vesicle equivalent. The nitrogen-fixing nodule is the site of intensive metabolic exchange. The fixed ammonium is assimilated into glutamate and glutamine by the plant and translocated to the shoot as glutamate, glutamine, citrulline, asparagine, or ornithine, depending on the host species (Persson and Huss-Danell 2009).

Actinorhizal plants perform extremely important ecological roles and are widely used for afforestation/reforestation of harsh sites. Many actinorhizal plants are also capable of forming mycorrhizal associations, and this sort of a tripartite symbiosis (host plant-*Frankia*-mycorrhiza) gives them a proclivity to grow on marginal and poor soils (Dawson 2008). Some species are also adapted to flooded and arid situations, besides contaminated soils, and extreme pH and high salinity conditions (Santi et al. 2013). Casuarinaceae and Betulaceae are the most widely planted families of actinorhizal plants around the world for rehabilitation of degraded lands. For example, *Casuarina* spp. are planted to stabilize coastal and desert dunes, and for reclamation of salt-affected soils as well as in intercropping systems (Diem and Dommergues 1990). *Alnus*, a large genus of about 35 species, and *Hippophae*, the genus of sea-buckthorns renowned for their nutritious berries and belonging to the families of Betulaceae and Elaeagnaceae, respectively, are popular in many parts of the northern temperate zones.

Two species of *Coriaria,* the sole genus in the family Coriariaceae, are known to be valuable components in agroforestry systems. *C. sinica*, a deciduous fast-growing bush, is widely planted in Hunan, China, as a source of green manure and feed for silkworms. The other species *C. arborea*, when grown as an understory species in plantations of *Pinus radiata* in New Zealand, is reported to be a prolific N_2-fixer. Research into the biology of the actinorhizal symbioses is, however, poorly developed and is generally hampered by the slow growth rate of the microsymbiont and its

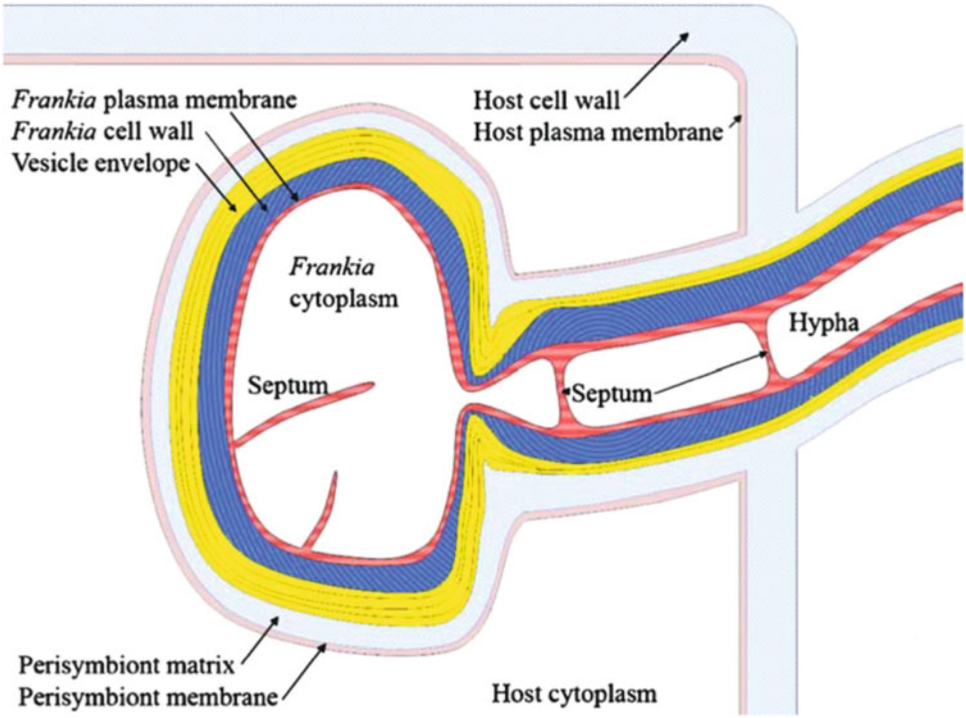

Figure 17.5. Schematic drawing of part of an *Alnus* nodule cell with a *Frankia* hypha differentiated into a symbiotic vesicle. The *Frankia* cytoplasm is surrounded by *Frankia* plasma membrane, *Frankia* cell wall and *Frankia* envelope. Note that the host plasma membrane is continuous with the membrane surrounding *Frankia*, the perisymbiont membrane. The perisymbiont matrix (older term: capsule) is contiguous with the plant cell wall and has a chemical composition with similarities to that of a primary plant cell wall. Note also that the envelope is thicker, has many more layers, around the symbiotic vesicle than around the hypha. Adapted from Persson and Huss-Danell (2009) the drawing is not to scale. Reproduced with permission from Springer

inability to be transformed in culture (Lindström et al. 2010). The economic importance of actinorhizal plants is also generally less than that of legumes, although *Casuarina* and some other species have been extensively used for reclaiming degraded sites.

17.5 Symbiotic Nitrogen Fixation (SNF) in Woody Perennials

17.5.1 Estimates of SNF by Trees

Quantifying the magnitude of BNF is a key for the effective management of agroforestry systems. Many efforts, employing several methods, have been made in this area and several estimates are available; the recent ones of the quantity of N_2 fixed by leguminous trees from different parts of the world, are summarized in Table 17.2. The data presented in this table, however, show wide variability (ranging from less than 1 to more than 200 kg ha^{-1} yr^{-1}). Reviewing the literature, Nygren et al. (2012) reported that the percentage of N_2 derived from the atmosphere (Ndfa) varied greatly among tree species, ranging from 5 % for *Calliandra calothyrsus* (Ståhl et al. 2002) to as high as 92 % for *Gliricidia sepium* (Nygren et al. 2000). Other workers too suggested that SNF in tree systems might range from about 10% to nearly 100% of the total nitrogen used by the host plant, which might be about 200 kg N ha^{-1} year^{-1} (e.g., Khanna 1998; Fisher and Binkley 2000; May and Attiwill 2003).

Table 17.2 Annual rates of nitrogen fixed by prominent leguminous tree species

Species	Study country	Stand age (years)	Rate of N fixation (kg ha^{-1} year^{-1})	Reference
Acacia alata			1.6	Hansen et al. (1987)
Acacia angustifolia	Zimbabwe	2	61	Chikowo et al. (2004)
Acacia caven	Chile	6	9.5	Aronson et al. (2002)
Acacia dealbata	Australia	2	12–32	Adams and Attiwill (1984)
		5	50	May and Attiwill (2003)
		50+	2.1	Pfautsch et al. (2009)
Acacia extensa	Australia	1–6	0.1	Hansen et al. (1987)
Acacia holoserica	Senegal	–	36–108	Peoples and Herridge (1990)
		1	4–11	Cornet et al. (1985)
Acacia holostera	Senegal	–	<12	Peoples and Herridge (1990)
Acacia magnium	Brazil	2.5	66	Bouillet et al. (2008)
Acacia mearnsii	Australia	7	0.75	Lawrie (1981)
Acacia melanoxylon	Australia	7	0.005	Lawrie (1981)
		50+	31.6	Pfautsch et al. (2009)
Acacia paradoxa	Australia	7	0.042	Lawrie (1981)
Acacia pellita	Australia	3	12	Langkamp et al. (1979)
Acacia pennatula	–	–	34	Roskoski et al. (1982)
Acacia pulchella	Australia	1–13	2.2	Monk et al. (1981)
		0.3–1	6	Hingston et al. (1982)
Acacia senegal	Sudan	4	7–12	Raddad et al. (2005)
Acacia vernicifula	Australia	–	38	Turvey and Smethurst (1983)
Albizia falcataria	Hawaii	–	100–200	Binkley and Giardina (1997)
Albizia lebbeck	Nigeria	1	60–120	Kadiata et al. (1996)
Albizia lebbeck	Nigeria	–	94	Danso et al. (1992)
Alnus incana spp. *rugosa*	USA	–	43	Hurd et al. (2001)
Calliandra calothyrsus	Australia	2	67–93	Stahl et al. (2002)
		1	76	Purwantari et al. (1996)
	Kenya	0.6	24	Gathumbi et al. (2002)
Casuarina equisetifolia	Puerto Rico	2	82–94	Parrotta et al. (1994a)
	Senegal	3	15	Mariotti et al. (1992)
Erythrina fusca	Costa Rica	1–2	80	Leblanc et al. (2007)
Erythrina lanceolata	Costa Rica	6	82.5	Salas et al. (2001)
Erythrina poeppigiana	Costa Rica	1–2	60–160	Leblanc et al. (2007)
Gliricidia sepium	French Antilles	8	147	Dulormne et al. (2003)
	Nigeria	–	108	Danso et al. (1992)
	Indonesia	1.3	700	Catchpoole and Blair (1990)
	Sumatra	1	35–38	Hairiah et al. (2000)
	Philippines	1.5	126	Ladha et al. (1993)
Inga edulis	Costa Rica	1–2	100	Leblanc et al. (2007)

(continued)

Table 17.2 (continued)

Species	Study country	Stand age (years)	Rate of N fixation (kg ha^{-1} $year^{-1}$)	Reference
Leucaena leucocephala	Malaysia	–	934	Peoples and Herridge (1990)
	Nigeria	1–4	238	Sanginga et al. (1996)
	Puerto Rico	1.5–3.5	71–74	Parrotta et al. (1996), (1994b)
	Tanzania	4	110	Högberg and Kvarnström (1982)
	Nigeria	–	304	Danso et al. (1992)
Prosopis glandulosa	USA	1	40	Shearer and Kohl (1986)
		–	25–30	Rundel et al. (1982)
Prosopis spp./*Acacia caven*	Chile	–	80–590	Urzúa (2000)
Robinia pseudoacacia	Austria	2	110	Danso et al. (1995)
Senna siamea	Nigeria	1–4	98	Sanginga et al. (1996)
Senna spectabilis	Nigeria	1–4	119	Sanginga et al. (1996)

Source: Mostly from Adams et al. (2010) to which some locations and species (e.g., Hurd et al. 2001, Parrotta et al. 1994, Mariotti et al. 1992, Sanginga et al. 1996 and Danso et al. 1995) were added

Tropical NFT species such as *Albizia*, *Calliandra*, *Gliricidia*, *Leucaena*, *Inga*, and *Prosopis*, notably *Leucaena*, are known to have high rates of fixed N_2 (Adams et al. 2010). During the 1980s and 1990s, several studies were initiated in the tropics to estimate the N_2 fixation potential of *L. leucocephala*. These included the use of acetylene reduction assay (Högberg and Kvarnström 1982), difference method (Sanginga et al. 1988), and ^{15}N dilution technique (Sanginga et al. 1989); and, values ranging from 100 to 500 kg N ha^{-1} yr^{-1} were reported. Sanginga et al. (1996), Danso et al. (1992), and Peoples and Herridge (1990) also suggested very high N_2 fixation rates (238, 304, and 934 kg N ha^{-1} yr^{-1}, respectively) for this species. The high N_2-fixing potential of *L. leucocephala* is partly due to its abundant nodulation under favorable soil conditions. Reported nodule dry weights were as high as 51 kg ha^{-1} in a stand of 830 trees ha^{-1} (Högberg and Kvarnström 1982) and 63 kg ha^{-1} in a stand of 2,500 trees ha^{-1} (Lulandala and Hall 1986). Wall (2000) reported actinorhizal symbiotic fixation of N_2 in the range of 240–350 kg N ha^{-1} yr^{-1}. These enormous variations in the quantities of nitrogen fixed by NFTs reflect not only the high N_2 fixing abilities of some species but more pointedly, the enormous experimental variability in the conditions of the studies (as discussed in the following sub-section). Sutherland and Sprent (1993) stated that the values reported are often overestimated and the quantities fixed are generally lower than 30–50 kg N ha^{-1} yr^{-1}, implying that SNF estimation procedures in agroforestry systems are not rigorous.

17.5.2 Factors Affecting SNF by Woody Perennials

A myriad of factors can influence the results of SNF such as those included in Table 17.2. Estimates vary even for the same species at the same location. Host genotype (cultivar, provenance), bacterial strain, and its efficiency, and, certainly, the estimation methods used are critical determinants (Section 17.6). Besides, the presence or absence of efficient rhizobial strains in the soil (symbiotic factors), environmental factors like soil moisture and acidity or residual soil nitrogen and phosphorus contents, and management practices play a key role in determining the magnitude of N_2 fixation. Rates of SNF are also influenced by NFT stocking levels, stand age and growth of the host plants, the degree of nodulation, and mycorrhizal associations. Several authors have reviewed the literature on these and related aspects (e.g., Danso et al. 1992; Sanginga et al. 1995; Binkley and Giardina 1997; Fisher and Binkley 2000; Brockwell et al. 2005; Forrester et al. 2006; Islam and Adjesiwor 2018).

Perhaps the most important factor that influences SNF is the host tree genotype. As can be seen from Table 17.2, tree legumes differ profoundly concerning the scale of SNF. Based on the N_2-fixation potential (NFP or the highest N_2-fixing activity of a given species when no limiting factors operate), Dommergues (1987) classified NFTs into two broad categories: species with high NFP, i.e., those that were estimated to fix between 100 to 300 (occasionally up to 500 or more) kg N $ha^{-1}yr^{-1}$; e.g., *Leucaena leucocephala, Calliandra* spp.*, Acacia mangium, A. auriculiformis, A. crassicarpa, A. mearnsii, Gliricidia sepium, Sesbania* spp., *C. equisetifolia,* and *C. cunninghamiana*; and species with low NFP (SNF less than 20 kg N ha^{-1} yr^{-1}); e.g., *Acacia raddiana, A. senegal,* and *Faidherbia albida*, while others could be treated as intermediates. Genotype and cultivar differences and seeding ratios (stocking levels in intercropping systems) also profoundly influence the NFP of herbaceous leguminous crop species (Thilakarathna et al. 2016a; Islam and Adjesiwor 2018). Such information, however, is rarely available for tree legumes.

Symbiotic factors such as specificity and promiscuity of rhizobia in nodulating various host plants too have attracted the attention of scientists. Inoculation with the appropriate strains of *Rhizobia,* therefore, holds considerable promise in optimizing N_2 fixation rates (Section 17.8). Although it is thought to have important practical implications for the manipulation of the symbiosis between legumes and rhizobia to enhance nodulation and improve N_2 fixation, such information is also somewhat scarce for tree crops, except probably for *L. leucocephala* and a few acacias (Diouf et al. 2003; Brockwell et al. 2005).

The prominent environmental factors affecting the complex process of legume SNF are soil nitrogen concentration, availability of other essential plant nutrients, soil temperature, and soil water content. Besides, soil salinity, soil pH, and the nature of the soil microbes also are likely to influence NFP, regardless of how effective a rhizobial strain might be (Peoples et al. 1995; Giller 2001). However, quantitative data on the effects of the environment and agroforestry management on SNF are generally scarce. While some authors have observed that nitrogenous fertilizers increased N_2-fixation by *Alnus* species (e.g., Binkley et al. 1994; Baker et al. 1997), several others have reported decreases in the total N_2 fixed or *Ndfa* when soil nitrogen availability is augmented (e.g., Baker et al. 1994; Dommergues 1995; Binkley et al. 2003). According to Maróti and Kondorosi (2014), nitrogen starvation of the host plant triggers SNF. This is because enhanced mineral nitrogen in the root zone inhibits legume nodulation and nitrogenase activity as it costs less energy for the legumes to absorb nitrogen from soil than fix it through the SNF route. Consistent with this, Turk et al. (1993), based on pot experiments, reported that enhanced soil nitrogen availability depressed inoculation response of A. *auriculiformis, A. mangium,* and *A. mearnsii.* Nevertheless, a certain initial concentration of mineral nitrogen in the root zone will stimulate nodule development and N_2 fixation, implying the need for modest doses of fertilizer N_2 application during the establishment phase of the legume crop. Usually defined as "starter N doses," such nutrient enhancements are variable with species, cultivar, and/or growth conditions.

Other elements including phosphorus and micronutrients (especially molybdenum, iron, and sulfur) are essential for sustaining reasonable levels of SNF. Early workers (e.g., Evans and Russell 1971) observed that high levels of both molybdenum and cobalt are needed for improved nitrogenase activity. Likewise, Lesueur and Diem (1997) showed that the *A. mangium/ Bradyrhizobium* association had a large and continuous requirement for exogenous iron to promote nodulation and N_2 fixation.

Tree management practices constitute another important determinant of SNF. In *Erythrina* *lanceolata* trees, for example, complete pruning every six months and *ca*. 50% pruning every three months exerted a negative effect on SNF (Salas et al. 2001). The $\delta^{15}N$ values (an index of the relative abundance of the two stable isotopes of N, $^{15}N:^{14}N$) under the complete pruning regime suggested a low N_2 fixation rate, while nodulation was almost zero. Nodulation of *Erythrina poeppigiana* under complete pruning treatment, however, recovered after a lag period of 10 weeks under the humid tropical conditions of Costa Rica (Nygren and Ramírez 1995). Common legume trees such as *G. sepium* and *C. calothyrsus* (Peoples et al. 1996; Nygren et al. 2000) have the potential for rapid recovery after pruning disturbances.

Ecological conditions also may influence SNF. Nygren et al. (2012) reported that annual N_2 fixation was the highest for improved fallows and protein banks (300–650 kg N ha^{-1}), with an average value of 246 kg ha^{-1} for 16 different agroforestry systems. In the arid soils of Africa, Diem and Dommergues (1990) reported that *C. equisetifolia* fixed an average of 15 kg N ha^{-1} $year^{-1}$. But in temperate climates, nitrogen-fixation in actinorhizal plants could be of the order of about 300 kg N ha^{-1} yr^{-1} (Wheeler and Miller 1990). The bottom-line is that SNF is influenced by an array of factors such that the reported values are extremely site-specific, and detailed information on many such factors are not available for most tree-based systems.

17.5.3 Mycorrhizal Infection of Legume Roots to Stimulate Nodulation

Rhizobia and mycorrhizal fungi can form tripartite associations with legumes. Many plant species benefit from such symbiotic associations, mainly because of the potential of the fungal mycelia to "act as conduits for plant nutrients, taken up from infertile soil that would be otherwise inaccessible to the plant" (Brockwell et al. 2005). Indeed, such mycorrhizal associations act as extensions of the fine root systems and augment nutrient uptake under harsh situations. Experimental studies indicate that *A. mangium* inoculated with both mycorrhiza and rhizobia showed enhanced growth (Dela Cruz and Yantasath 1993); and inoculation with a rhizobial strain and the endomycorrhiza, *Glomus fasciculatum,* promoted growth of *Acacia nilotica* (Lal and Khanna 1996). Apart from growth-promoting effects, combinations involving mycorrhiza and root-nodule bacteria may also synergistically stimulate N_2 fixation in legumes growing on P deficient soils (Bâ et al. 1996). This is because the mycorrhizal mycelial network may increase the absorption and solubilization of P by translocating P in the soil to rhizobia located on plant nodules (Bonfante and Anca 2009; Vega et al. 2010). It seems that the tripartite relationships including rhizobia can be synergistic, but the conditions required for that to occur are not clearly defined.

17.6 Measurement of Symbiotic Nitrogen Fixation

The importance of accurate estimation of BNF under field condition has been well recognized; but precise, cost-effective, and easy-to-use methods are, unfortunately, not available. Several descriptions of the methods for measuring N_2 fixation do exist, however. The commonly used methods are discussed here briefly. Almost all these methods have been developed for estimating the NFP of herbaceous field crops; efforts to adapt and develop them for agroforestry applications have been limited.

17.6.1 Acetylene Reduction Assay (ARA)

The use of ARA as a diagnostic tool started in the 1960s following the discovery (Dilworth 1966) that nitrogenase could reduce acetylene (C_2H_2) to ethylene (C_2H_4). It is a convenient, indirect method to evaluate the activity of the nitrogenase enzyme system. Typically, freshly excised roots, bacterial cultures, soil samples, or root nodules are incubated in an atmosphere enriched with

5–10% C_2H_2. At this concentration, the nitrogenase ceases to reduce N_2 and preferentially uses acetylene as a substrate, owing to its high affinity. As the microbes do not utilize the reaction product, C_2H_4, it accumulates in the vessel. After a short incubation period (1 to 2 h), a sample of the gas is removed and the C_2H_4 produced is determined by gas chromatography. Acetylene-reduction assays are converted to estimates of N_2 fixation using a conversion ratio 3:1, i.e., one mole of C_2H_4 being equivalent to 1/3 mole of N_2 reduced (fixed). It is now realized that this ratio is profoundly variable and therefore must be checked for each system. ARA measures the instantaneous nitrogenase activity and it is appropriate for free-living diazotrophs in a culture medium. It has limited application for higher plants, and at best, can yield some qualitative estimates (Brockwell et al. 2005).

17.6.2 The Difference Method

This is the classical agronomic method based on the fallacious assumption that the N_2-fixing plants derive their entire nitrogen from symbiotic fixation. The N_2-fixing and non-N_2-fixing plants are grown under similar conditions, and the difference in N contents of the non-N_2-fixing and the N_2-fixing species is taken as nitrogen derived from N_2 fixation (Williams et al. 1977). The method is considered accurate and reliable under controlled conditions using a nitrogen-free substrate but has serious limitations for applicability under field conditions (Brockwell et al. 2005). Even when a non-nodulating isoline of the test legume is used as the control, field results are somewhat unreliable (Boddey et al. 1984). The underlying assumption that the N_2-fixing plants derive their entire nitrogen from symbiotic fixation, and estimates based simply on legume nitrogen yield are inaccurate. A more precise estimate based on crop nitrogen accumulation is feasible when the soil nitrogen contribution to the total legume nitrogen is correctly determined. This can perhaps be accomplished by growing a companion non-N_2-fixing control crop in the same soil and under identical conditions as the legume (usually in an adjacent plot).

17.6.3 The ^{15}N Isotopic Methods

Isotopic techniques offer versatile tools for the direct estimation of SNF, and methods using such techniques were developed as early as 1957 (e.g., Burris and Wilson 1957; Burris 1972). Use of stable isotopes at naturally occurring levels can provide information on the nature of N_2-fixation. Nitrogen-15 (^{15}N), the rare and heavy isotope of nitrogen is predominantly used for this purpose. Two distinct categories of the ^{15}N-isotopic technique are available: artificial ^{15}N enrichment of the soil and natural enrichment (natural abundance) of ^{15}N in the soil. These methods generally segregate nitrogen content of legumes into (i) nitrogen derived from soil pool, and (ii) nitrogen derived from the atmosphere.

The ^{15}N enrichment (Dilution) Technique: Most soils are enriched with ^{15}N in comparison to the proportion of $^{15}N/^{14}N$ in the atmospheric N_2 pool. By administering a dose of ^{15}N-enriched nitrogenous salt, the level of natural enrichment of plant-available nitrogen in the soil can be further augmented. The method, popularly known as the isotope dilution technique, involves growing N_2-fixing plant and a non-fixing control in the soil to which a small quantity of ^{15}N has been applied as labeled nitrate or ammonium. The control or reference plant, which is completely dependent on soil nitrogen for growth, should have identical ^{15}N content as that of soil nitrogen. However, the plant deriving part of its nitrogen requirements from the atmosphere will have a lower ^{15}N signature, because the N_2-fixing plant obtains nitrogen from two sources (soil and atmosphere) and the non-N_2-fixing plants absorb only labeled soil nitrogen. The percentage of the plant nitrogen derived from N_2 fixation is calculated from the ^{15}N atom percent in excess in non-N_2-fixing than in the N_2-fixing plant. The method has been used to evaluate N_2 fixation in several tree species (IAEA 1998, Brockwell et al. 2005).

A fundamental assumption of the ^{15}N enrichment technique is that the isotope incorporated into soil nitrogen is equally available to both N_2-fixing and the non-N_2-fixing reference plant. It also assumes that the legume and reference plant explore identical soil nitrogen pools with similar $^{15}N/^{14}N$ composition. If the N_2-fixing test plant and its non-N_2-fixing control have similar growth characteristics, this technique can give reliable estimates of the proportion of legume N_2 derived from the atmosphere. However, these assumptions are difficult to attain, especially when the plants have dissimilar growth attributes. This technique also requires sophisticated and costly instrumentation (e.g., mass spectrometer), besides expensive isotopes. Another drawback is that the applied nitrogen, particularly nitrate, may interfere with the nodulation process. To ensure that the addition of ^{15}N-labelled material does not affect N_2 fixation, low rates of nitrogen application (< 5 kg N ha^{-1}) are usually recommended (Peoples et al. 1989). If a carbon source is being used to immobilize added ^{15}N or if ^{15}N-labeled organic matter is being added, it is also important that there is no stimulation of N_2 fixation due to an effect of the labeling treatment on soil nitrogen availability. Moreover, if the soil nitrogen is low, the non-fixing reference plant may exhibit slower growth than the test plant and thus not be an analogous control. Likewise, with increasing SNF, the abundance of ^{15}N in the N_2-fixing plant drops as nitrogen absorbed from the soil is "diluted" by atmospheric N_2 of lower ^{15}N abundance originating from root nodules (Peoples et al. 1989). Besides, the N_2-fixing legumes may depress the $\delta^{15}N$-signal of the soil nitrogen-pools, in turn contributing to anomalous results; this is the so-called "^{15}N-dilution problem" (Gehring and Vlek 2004). The main advantage, however, is that the "method provides a *time-averaged* estimate of the proportion of legume nitrogen derived from N_2 fixation" (Peoples et al. 1989).

The Natural ^{15}N Abundance Method: This method was developed as an alternative to the isotope dilution technique and other methods described earlier, which are not considered suitable for the appraisal of SNF in natural ecosystems (Shearer and Kohl 1986; Boddey et al. 2000; Lindström 2011). Natural ^{15}N abundance works on the same premise as that of isotope dilution technique, except that soil is artificially enriched with ^{15}N above background levels in the dilution method. The underlying principle is that biological systems, like the nitrogenase enzyme, differentiate between isotopes and prefer the lighter forms; nitrogenase favors the more plentiful ^{14}N isotope to the heavier ^{15}N. Consequently, an N_2-fixing plant will have a higher proportion of ^{14}N than ^{15}N. However, soil N_2 frequently contains slightly more ^{15}N than atmospheric N_2. Nitrogen derived from N_2 fixation will thus have a slightly lesser ^{15}N signature than N_2 originating from the soil so that the natural ^{15}N abundance is lower in well-known N_2-fixing plants than in non-N_2-fixing ones (Knowles 1983). From the measure of the natural ^{15}N abundance in N_2-fixing and non-N_2-fixing plants, it is possible to calculate the fraction of the plant nitrogen derived from N_2 fixation. Being a non-destructive method, natural ^{15}N abundance is thought to be the most appropriate for estimating SNF in natural ecosystems and farming systems involving trees.

In this method, the investigators derive $\delta^{15}N$ values of the NFT tissue sample by comparing with an absolute abundance ratio obtained from atmospheric N_2. A positive $\delta^{15}N$ value is suggestive of a sample enriched with ^{15}N relative to natural abundance, while a negative $\delta^{15}N$ denotes a lower proportion of the heavy ^{15}N (Dawson et al. 2002). For plants entirely dependent on N_2 fixation for growth, the $\delta^{15}N$ signature of the total N may differ from that of atmospheric N_2, which is taken as zero. For outcomes to be important, the ^{15}N natural abundance approach requires the $\delta^{15}N$-signals of well-known N_2-fixers to be considerably less than that of the reference or control plants (Gehring and Vlek 2004). Högberg (1997) postulated that for precisely estimating BNF, this method necessitates at least a 5% difference between the mean $\delta^{15}N$-signals of putative (known) N_2-fixers and the reference plants. That is, a significant difference between the $\delta^{15}N$ value of the NFT tissue and the equivalent tissue type of a reference tree is necessary for the successful application of the natural abundance method (Boddey et al. 2000; Forrester et al. 2007). Lower $\delta^{15}N$ values of a putative N_2-fixer compared to a non-N_2-fixing control plant with higher $\delta^{15}N$ mirrors the enrichment of the available soil N. It enables the computation of the proportion of Ndfa by N_2-fixing plants (Munroe and Isaac 2014).

The ^{15}N natural abundance method is widely employed to estimate the NFP of trees in natural ecosystems (Domenach et al. 1989; Hamilton et al. 1993) and agroforestry systems (Sanginga et al. 1995; Nygren and Leblanc 2009; Isaac et al. 2011; Munroe and Isaac 2014). Just as with the isotope dilution method, one of the main weaknesses of this technique is the need to use non-N_2-fixing plants to assess legume ^{15}N uptake (Unkovich et al. 2008; Munroe and Isaac 2014). Being a prerequisite that both N_2-fixing and non-NFT species exploit the same soil layers and assimilate the same sources of nitrogen, the selection of the reference plant possessing such characteristics is critical. Finding a non-N_2-fixing reference species with identical root distribution, temporal nitrogen uptake pattern, and preferences for the uptake of soil nitrogen as the N_2-fixing species, nevertheless, poses a major challenge (Högberg 1997).

The main advantage of the ^{15}N natural abundance method is that since it requires no pre-treatment with ^{15}N, the technique can be applied to existing experiments or trees growing in plantations or even natural forests. It also does not require costly ^{15}N labeled fertilizers. This method, however, requires access to an isotope ratio mass spectrometer and delicate and fastidious manipulations, but the results are as reliable as those obtained from the ^{15}N-dilution method (Bergersen 1988).

17.6.4 Xylem-Solute Method

Xylem nitrogen-solute composition of fully symbiotic plants and non-nodulated plants that are dependent upon soil nitrogen are monitored in this method. It is based on the premise that since the legumes translocate the products of N_2 fixation either as ureides (allantoic acid and allantoin) or amides, the higher the relative proportion of these compounds to nitrates and amino compounds in the xylem sap, the greater will be the reliance of the host plant on rhizobially fixed N_2. This principle has led to assaying the proportion of ureides and/or amides in the nitrogenous compounds in the xylem sap for estimating SNF (McClure and Israel 1979; Herridge 1982). Although accurate estimates of SNF can be obtained by this method (Herridge and Peoples 2002), the amide assay is generally considered less sensitive than the ureide assay. Besides, xylem sap extraction is cumbersome, especially in woody perennials, and often a lethal sampling is required, which may be appropriate for herbaceous plants but not trees.

17.6.5 Other Methods for Comparing Nitrogen Fixation

Quite a few indirect methods are also available for determining SNF. They generally provide a subjective appraisal of the response to inoculation or the ability of a plant to fix N_2. Examples include nodulation indices such as earliness of nodulation, nodule number and fresh or dry weight and leghemoglobin content of the nodules, besides distribution and longevity of the nodule population, and visual nodulation scores. Such methods, however, are generally considered ill-suited for making quantitative estimations of the amount of N_2 fixed. The red or pink nodule interiors because of the leghemoglobin content are, at best, indicators and not a testimony of SNF. Moreover, total nitrogen accumulation of the whole plant may offer only a crude indication of SNF, and this method will overestimate N_2 fixation.

Empirical models and dynamic mechanistic simulation models have also been tried to estimate legume BNF. The dynamic simulation models are claimed to be preferable for quantifying SNF because of their capability to simulate the response of N_2 fixation to a wide range of environmental variables and legume growth status (Liu et al. 2011). However, such methods are yet to gain wide acceptability. In summary, perhaps it is correct to state that there is yet no single “correct” technique for measuring BNF, and “no one technique will offer an accurate measure of N_2 fixation for all legumes grown in any soil under diverse environmental conditions” (Peoples et al. 1989). Each method has distinct advantages as well as shortcomings. According to Giller (2001), despite the many shortcomings, isotope-based approaches are the best for quantifying N_2-fixation, provided the assumptions of the methods are satisfied.

17.7 Transfer of Symbiotically Fixed Nitrogen

Most of the N_2 fixed by legumes may be used to satisfy the current nitrogen demands of the host plant. Yet a significant part of the fixed N_2 may be transferred to the associated non-N_2-fixing plants in crop combination systems or released to the residual soil nitrogen pool. The BNF-derived N_2 can, thus, help reduce the dependence on synthetic nitrogenous fertilizers in crop production and provide substantial economic and environmental benefits. Reviewing the available information on this topic, Lassaletta et al. (2014) found that soil-nitrogen-use efficiency (NUE) increased exponentially with increasing levels of BNF but decreased linearly with increasing levels of synthetic nitrogen inputs. A major uncertainty, though, is the proportion of the biologically fixed N_2 that is available to neighboring or succeeding non-N_2-fixing plants.

17.7.1 Nitrogen Transfer Pathways

Despite the significance, especially in agroforestry systems, of the extent of “recovery” of fixed-N_2 by associated crops, field-based studies on the topic have been very few. The challenges to be faced in such investigations are of many types and forms. One that is unique to systems involving woody perennials is that the use of juvenile trees in such studies may be inappropriate because N_2-fixation in trees generally decreases with age (Isaac et al. 2011). Thus, there is considerable uncertainty about not only the extent of N_2-fixation (Section 17.5.1) but the extent to which the fixed N_2 is transferred to companion species during the current and subsequent seasons.

The transfer of symbiotically fixed N_2 to associated non-legume plants involves three main processes: (1) litter decomposition and N mineralization (2) root-to-root direct transfer via exudation of organic compounds, and (3) transfer mediated by common mycorrhizal networks or CMN (He et al. 2009; Munroe and Isaac 2014; Fellbaum et al. 2014; Thilakarathna et al. 2016b). The relative proportion of nitrogen transported by these processes is highly variable among agroecosystems and it is also influenced by various tree and crop management practices.

Decomposition of the litter (aboveground litter, pruning residues, roots including the sloughed off nodules and fine roots, etc.) is commonly considered as the main pathway of nitrogen transfer from NFTs to associated non-N_2 fixing species, especially where the aboveground biomass of tree legumes is recycled as in alley cropping systems (Munroe and Isaac 2014). However, some studies have shown that direct belowground transfer without transformation can also provide substantial inputs of nitrogen for the non-N_2 fixing species. For example, nitrogen transfer from the tropical legume, *G. sepium* to yellow-bluestem grass (*Dichanthium aristatum*) was reported to be mainly via root exudates (Jalonen et al. 2009). Low-molecular-weight nitrogenous compounds, such as ammonium, nitrate, and amino-acids (Paynel and Cliquet 2003), exuded by legume roots may be absorbed by the companion plants before these compounds are immobilized by soil microbes (Munroe and Isaac 2014). Rhizodeposition through the decomposition of the nodules and roots, however, represents the main pathway of nitrogen transfer in many herbaceous crops (Islam and Adjesiwor 2018). Given the potential for the transfer of these compounds, root exudation has been studied in a range of tropical agroforestry systems. The consensus emanating is that exudation of nitrogen-rich molecules from N_2-fixing plants and subsequent uptake by closely associated root systems represents a smaller (compared to aboveground inputs) but substantial pathway (Islam and Adjesiwor 2018). The direct transfer of nitrogen via CMN is perhaps the smallest mode of transfer and one that is extremely hard to estimate. Nygren and Leblanc (2015), however, observed that CMN is the most likely pathway for the direct nitrogen transfer from *Inga edulis* to *Theobroma cacao*. According to Thilakarathna et al. (2016a), both exudates of soluble nitrogen compounds and transfer mediated by mycorrhizae are faster than the decomposition of nodules and roots and the associated transfer in herbaceous mixtures. In short, all these modes play an important role in the nitrogen economy of agroforestry systems and the relative importance of each is situation-specific.

17.7.2 Factors Affecting Nitrogen Transfer

Environmental factors such as water, temperature, and light exert both direct and indirect effects on nitrogen transfer dynamics given the influence of such factors on N_2-fixation and decomposition and mineralization processes (Thilakarathna et al. 2016b). Soil moisture probably has the greatest influence on organic matter decomposition. Moisture stress will adversely affect both the mineralization of fixed N_2 and the uptake of mineralized nitrogen by plants. It will also stimulate nodule senescence, implying that more nodule biomass will be available for mineralization following an episode of moisture stress. Nitrogen being highly soluble, excess water can leach out substantial quantities of nitrogen compounds from the rooting zone of plants, and under anoxic conditions, it may result in gaseous losses as N_2O, through denitrification.

Optimum light (quality, quantity, and duration) and temperature regimes will have a direct effect on photosynthesis and thus will promote N_2 fixation and transfer. Rainfall and evapotranspiration are also key climatic factors controlling N dynamics. In a silvopastoral study involving *G. sepium* and *D. aristatum* in Guadeloupe (French Antilles), it was found that an increase of 10% precipitation/day would prompt a 14 % rise in N released from the tree and a 10% increase in grass nitrogen uptake (Daudin and Sierra 2008). The authors also indicated that soil type plays a key role in shaping nitrogen transfer dynamics: high clay content may promote preferential uptake of tree-derived nitrogen by the grass.

The proximity of the N_2-fixing crop to the non-N_2-fixing component of the system is also an important factor. In a replacement series experiment involving teak (*Tectona grandis*) and *Leucaena leucocephala* in peninsular India, Kumar et al. (1998) found that teak growth increased as the relative proportion of leucaena in the mixture increased. Furthermore, Khanna (1997) reported a higher in-situ soil mineralization rate in a 2-year-old *Eucalyptus globulus* + *A. mearnsii* (1:1) mixture compared to that of an *E. globulus* monoculture in southeast Asia.

The interval for accruing the benefit from the N_2-fixing species to the associated non-N_2 fixing species has not received much attention. Khanna (1997) in the previously mentioned study found that *E. globulus* planted with *A. mearnsii* were taller than individuals grown in monoculture, from as early as 25 months of age onward. In mixtures of *Eucalyptus* × *robusta* and *C. equisetifolia* or *L. leucocephala,* Parrotta et al. (1996) found that *E.* × *robusta* saplings were taking up nitrogen fixed by both N_2-fixing species after two years. Available results, however, are not adequate to conclude when nitrogen transfer from the N_2-fixing plants (donors) to non-N_2-fixing crops (receivers) commences.

17.7.3 Methodological Considerations

Isotopic techniques have been used to characterize the transfer dynamics of nitrogen between plants in some agroforestry systems (see also Section 17.6.4). Labeling the nitrogen source with the stable ^{15}N isotope by leaf-feeding in which trace amounts of a label had been applied topically to the foliage and detecting the ^{15}N-enrichment has been the most commonly used method to monitor the fate of fixed-N_2 (Dawson et al. 2002; Nygren and Leblanc 2015). There have been issues, however, in using the technique with leguminous trees (Sierra and Daudin 2010). The distinctive spatial arrangement and morphological characteristics of perennial crops and NFTs within agroforestry systems may pose challenges for sampling as well as for the study of nitrogen transfer (Munroe and Isaac 2014), especially when ^{15}N labeling may result in differential enrichment in different tree parts (Jalonen and Sierra 2012). Furthermore, field-scale ^{15}N labeling is difficult and expensive (Rowe and Cadisch 2002). Given the obstacles associated with labeling large, mature trees via leaf feeding, juvenile trees in greenhouse studies have been widely used (Zeller et al. 1998; Kurppa et al. 2010). Such studies may provide useful information about the magnitude and mechanisms of transfer, but the extent to which they indicate actual nitrogen dynamics in the ecosystem remains unclear (Munroe and Isaac 2014).

While some authors have advocated the use of ^{15}N natural abundance method for quantifying the transfer of N_2 fixed from an NFT to non-fixing plants (e.g., Boddey et al. 2000), the use of that method could be problematic, given the sensitivity to fractionation of ^{15}N within the plant-soil system (Munroe and Isaac 2014). Using that technique, Snoeck et al. (2000) showed that, under field conditions, roughly 30% of the nitrogen effectively fixed by a legume (including biomass, roots, and root exudates) was transferred to the associated coffee bushes (*Coffea arabica*). The bottom line is that the magnitude of fixed N_2 transfer from NFTs is highly variable (0% to 73%; Thilakarathna et al. 2016b) and the choice of method to assess it is a key determinant of such variability.

17.7.4 Nitrogen Gains of Non-NFTs in Mixed-Species Plantations with NFTs

As discussed, significant quantities of N_2 are transferred from the NFT components to the non-NFT components growing in association. Plants that are incapable of fixing N_2, therefore, can benefit from the N_2 assimilated by associated N_2-fixing plants when dead plant tissues and microbial cells decompose and cycle through the ecosystem, or through mycorrhizal connections between root systems when both species form tripartite symbioses, or via root exudation (Section 17.7.1). Silvicultural studies involving mixtures of NFTs and non-NFTs in intimate combinations have highlighted the beneficial effects of such mixtures. *Eucalyptus* (non-N_2 fixing) and *Acacia* (N_2 fixing) mixtures are a case in point. *E. globulus* and *A. mearnsii* in 1:1 proportion were twice as productive as *E. globulus* monocultures growing on the same site in Victoria, Australia (Forrester et al. 2007). In an additive series (1:1 ratio) experiment at five sites in Brazil and Congo with varying densities of *A. mangium* for the same density of *Eucalyptus grandis* or *E. urophylla* × *grandis*, Bouillet et al. (2013) also found that mixtures were more productive than monocultures. The positive balance between facilitative effects and competition between species may explain such beneficial effects. Increased growth and other favorable traits in mixtures containing NFTs are often due to the improved N_2 availability and uptake (Forrester et al. 2006, 2007; Bouillet et al. 2008; Adams et al. 2010). Although such studies have been initiated only in the recent past, the beneficial effects including increased biomass production, soil carbon sequestration, microbial diversity, and soil fertility have been reported (e.g., Paula et al. 2015). Overall, the integration of NFTs with non-NFTs could be an attractive option.

17.8 Managing the Microsymbionts in Agroforestry

17.8.1 Legume Inoculation

The potential for benefitting from the symbioses with effective rhizobia in agroforestry is vast, but it remains highly underexploited. Field studies conducted in the tropics show that, but for a few cases, actual N_2 fixation is inadequate to sustain the soil nitrogen pool when crops and wood products harvested export nitrogen actively

(Danso et al. 1992; Hardarson 1993). Many soils do not have an adequate population density of rhizobia to cause nodulation of newly planted NFTs (Thrall et al. 2001). Therefore, legume inoculation is a significant strategy for improving plant productivity and soil nitrogen balance, especially in agroforestry. However, only relatively few studies (mostly nursery-based) have evaluated the impacts of rhizobial inoculation on NFTs. Furthermore, all grades of host-rhizobia specificity, ranging from broadly promiscuous to highly specific organisms occur in nature. Species in the latter category benefit from inoculation when they are introduced to new environments where soils lack the specific N_2-fixing bacteria.

A related issue is the native N_2-fixing bacterial populations. The size and natural range of rhizobial populations in field soils vary profoundly. Odee et al. (1995) observed populations as high as 2.3×10^5 per g of soil in Kenya. Conversely, rhizobial counts were very low or even absent in certain degraded sites of Australia (e.g., Thrall et al. 2001). Turk et al. (1993) reported that when populations are small (e.g., <50 per g) and with low efficiency, rhizobial inoculation will result in enhanced N_2 fixation. Under such situations, it is important to obtain elite strains of rhizobia for efficient SNF (Figueiredo et al. 2008). However, when the rhizobial population in the soil is large (e.g., >1000 cells per g), introduced strains would possibly encounter stiff competition from the resident organisms, leading to a lack of response to inoculation *per se*. Thus, the size and composition of the resident rhizobial populations and the nitrogen status of the soil are important factors that determine the success of introducing rhizobial strains into the soil (Singleton and Tavares 1986).

Inoculation, however, is a cost-effective strategy for attaining early high populations of the soil microbes in most situations. When the inoculant is applied to nursery soils immediately before seeding, a large population of effective rhizobia can be ensured in the rooting medium, stimulating quick nodulation and early onset of N_2 fixation. Inoculated seedlings also attain planting size more rapidly than uninoculated seedlings and, thus, save time in the nursery, besides ensuring better survival and early growth in the field (Brockwell et al. 2005). Also, the effective inoculant strains persist in the soil for many years and will be a potent source of inoculum for future plantations as well on such sites. Masutha et al. (1997), however, reported that for six promiscuous species of *Acacia* at two sites in South Africa, natural inoculation by native soil rhizobia was superior to artificial inoculation with rhizobial cultures, implying that the results of NFT inoculation studies are somewhat inconsistent.

Specific bacterial strains for inoculation: Bacterial strains specific to individual species/cultivars/provenances are often recommended for enhanced N_2 fixation efficiency. This will result in combining the most efficient N_2-fixing tree genotypes or provenances with the rhizobium or *Frankia* strains (Sougoufara et al. 1992). Strain selection, however, is a challenging task. Although a considerable number of studies were conducted on herbaceous crops, studies matching NFT genotypes with bacterial strains are rare. Brockwell et al. (2005) cataloged some principles for harmonizing the choice of acacia species and its microsymbionts. A list of parameters appropriate for rhizobial strains for legume inoculation is shown in Table 17.3. The bottom-line is that while it would not be practical to identify a special inoculant for each NFT, a rational approach to strain selection is essential for the production of inoculants. Furthermore, there appears to be scope for selecting strains that are adapted to harsh conditions. However, only very few studies are available on the environmental tolerance of N_2 fixing organisms concerning NFTs. In one such study, Surange et al. (1997) identified acacia rhizobia that tolerate salt concentrations up to 5.0% and pH levels up to 9.0.

17.8.2 Establishment of the Microsymbiont

Inoculation procedures generally aim at (i) augmenting inoculant survival during the non-rhizospheric phase, and/or (ii) hastening seed germination so that the non-rhizosphere period is shortened (Brockwell et al. 2005). This is because

Table 17.3 Characters considered desirable for inoculant strains and inoculant carriers

Strain characters for legume inoculants
1. Ability to form nodules and fix N on the target legume
2. A wide host range, i.e. the ability to fix N with a wide range of host genotypes
3. Ability to fix N across a wide range of environmental conditions
4. Ability to compete in nodule formation with populations of rhizobia already present in the soil
5. Ability to form nodules and fix N in the presence of soil nitrate
6. Ability to grow well in artificial media, in inoculant carrier and in the soil
7. Low mortality on inoculated seed
8. Ability to migrate from the initial site of inoculation
9. Ability to tolerate environmental stress
10. Ability to colonise the rhizosphere of the host plant
11. Ability to colonise the soil in the absence of a legume host
12. Genetic stability
13. Compatibility with agrichemicals
Properties of good inoculant carriers
1. High water-holding capacity
2. Non-toxic to rhizobia
3. Easy to sterilise by autoclaving or gamma irradiation
4. Readily and inexpensively available
5. Sufficiently adhesive for effective application to seed
6. Good pH buffering capacity
7. Good cation- and anion-exchange capacities

Source: Adapted from Brockwell et al. (2005)

in nature all rhizobial proliferation occurs in the rhizospheric region of the target species, on the root exteriors and particularly inside the nodules. They also reported that better inoculation success for acacias can be achieved by soil application than by applying it to the seed surface, and peat-based inoculants tend to survive better in soil than do liquid inoculants. Inoculation with rhizobial strains cultured in a peat carrier, therefore, is postulated as an efficient means of producing vigorous, well-nodulated, and N_2-fixing seedlings in nurseries. When such nursery-inoculated *A. mearnsii* seedlings were out-planted, their survival, growth, and benefit to companion plantings of *Eucalyptus nitens* (shining gum) were better than that of uninoculated seedlings (Brockwell et al. 2005).

In the case of containerized planting stock, inoculation with rhizobium is best achieved by spraying or drilling the inoculum directly into the container at the time of sowing, or mixing seeds and inoculum before sowing. When dealing with *Frankia*, it is advisable to mix the soil or substratum of the container with the inoculum because *Frankia*, like vesicular-arbuscular mycorrhizal fungi, is not mobile in the soil. In the past, pure cultures of *Frankia* were not used often on actinorhizal plants owing to the difficulty in isolating and maintaining such cultures. However, with advancements in *Frankia* inoculant technology, it is now possible to inoculate the actinorhizal plants with pure cultures of *Frankia* (Girgis et al. 1998).

Application of starter doses of nitrogen (together with P and K) on NFTs also has been recommended (Section 17.5.2). Soil acidity and associated factors (Al and/or Mn toxicity and Ca and Mo deficiencies), which affect many tropical soils, may retard N_2 fixation through the direct or indirect effects they have on the host plant and the symbiotic microorganisms. A case in point is *A. mearnsii*, which does not nodulate in the highlands of Burundi where soils have a low pH and a high content of exchangeable Al. The detrimental effects of soil acidity can be overcome by selecting acid-tolerant host plants (or provenances) and symbiotic microorganisms, an approach that has been adopted for *L. leucocephala* (Halliday and Somasegaran 1983); but recent reports on the topic are scarce. To control the effects of soil acidity, direct application of proper amendments to the soil or pelleting the seeds with calcium carbonate or rock phosphate in the case of direct sowing in the field are advocated. The acidity generated by N_2-fixing plants, in the long run, may lower the pH of weakly buffered soils, and periodic liming may be necessary to maintain high productivity (Franco 1984). Although pelleting has proved to be a high-value alternative for liming during the introduction and establishment of forage legumes in pastures (Williams 1984), in very acid soils with Al or Mn toxicity, pelleting alone cannot overcome the effects of acidity. Inoculating the NFT nursery stock with effective strains of rhizobia is a cost-effective measure to improve the vigor and N_2 fixation of seedlings in the field. Inoculated, well-nodulated seedlings survive better and grow faster after out-planting than uninoculated ones. However, proper selection of the microsymbiont strains, inoculation techniques, and balanced nutrition of the host plants are crucial for success.

17.9 Concluding Remarks

Remarkable progress has been attained in harnessing the benefits offered by the BNF technology since the 1980s. The initial enthusiasm and some promising efforts in capturing these benefits in agroforestry have, unfortunately, been not sustained. The majority of such initiatives included field-level evaluation of NFT cultivars and provenances and estimation of their nitrogen-fixing potential. The methods of such assessments, however, have not been rigorous or standardized such that the reported values are highly variable. This resulted in an undesirable situation of a euphoria-driven quest and enthusiasm for data on NFP of the widely promoted NFTs on the one hand and the lack of rigorous data on the other, which led to untested and non-validated "data" becoming publicized and even gaining (pseudo)authenticity by sheer repetition.

To date only a limited number of effective strains of *Rhizobium* that nodulate NFTs have been isolated: some of the best known are strains for *L. leucocephala;* others include the legumes *Acacia* spp., *Erythrina* spp., *Gliricidia sepium*, and *Inga* spp. There is still much work ahead for collecting microsymbiont strains for NFTs and then screening them for genetic compatibility, N_2 fixation effectiveness, and tolerance to environmental stresses, especially soil acidity, under field conditions. Similarly, *Frankia* strains associated with actinorhizal plants exhibit large variability in genetic compatibility and N_2 fixation capability. Molecular techniques are reportedly available to engineer new strains of *Rhizobium* and *Frankia* to contain multiple copies of the major genes involved in the symbiosis: genes of N_2 fixation and nodulation, and genes involved in the inter-strain competition.

The amount of nitrogen fixed by any NFT is related to its NFP, which is directly affected by the genotypes of both the host plant and the associated microsymbionts. The NFTs for agroforestry should not only have high NFP, but be adaptable to environmental stresses (of physical, chemical, and biological nature) that can realistically be expected of situations where agroforestry is practiced. Given the well-known inhibitory effect of high levels of soil (mineral) nitrogen on N_2 fixation, the NFTs and their symbionts in agroforestry systems should be engineered to continue fixing significant amounts of N_2 even when the intercrop receives nitrogenous fertilizers. The nitrogen transfer dynamics in agroforestry systems with perennial crops is another area that is of high priority. After all, high levels of BNF *per se* are of little practical value to the land-user unless the amounts so fixed are "transferred" and made available to the simultaneous and/or sequential companion crops in agroforestry systems. The potential and opportunities offered by BNF in agroforestry are, indeed, extremely promising. Success depends on how effectively the potential is harnessed and the opportunities are exploited.

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Soil Conservation and Control of Land-Degradation

18

Contents

Abstract

The concept of soil conservation has evolved over several decades to include both the prevention of soil loss and reduction of its productive capacity. Land degradation, an allied term, refers to any change or disturbance to the land perceived to be deleterious or undesirable. Both these terms are prominent components of soil health, a term that has received considerable prominence in recent times. The importance of tree-based land-use systems in protecting the soil has been convincingly demonstrated by the success of large-scale planting of trees as windbreaks to

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address the devastating wind erosion in the Great Plains of the USA in the 1930s. Thus, the relevance of agroforestry for soil conservation was recognized from the early days of agroforestry development. Similar to other major aspects of soil management such as soil organic matter and biological nitrogen fixation, several excellent resource materials are available on the details of developments in soil conservation. This chapter focuses on explaining the relevance and applicability of such known facts to agroforestry systems (AFS). The measurement of soil erosion by water and wind using the Universal Soil Loss Equation (USLE) and its revised version (RUSLE) and the reported rates of soil erosion under AFS are briefly described. Experiences with some agroforestry-based largescale field projects for the control of soil erosion and land degradation in different parts of the tropics and a note on biodrainage (tree planting for the amelioration of soil salinity and waterlogging) are also included. Efforts in soil conservation and land degradation control worldwide over the decades have shown that using plant canopies or residues as an effective land cover is one of the most successful ways of promoting soil conservation, for which agroforestry is an excellent option.

18.1 Introduction

Land degradation, including soil erosion, is one of the world's most pressing environmental problems. It is happening at an alarming pace, contributing to a dramatic decline in the productivity of croplands and rangelands worldwide. Globally, about 25 percent of the total land area has been degraded and 3.2 billion people are affected, especially rural communities, smallholder farmers, and the very poor. Several United Nations Agencies have raised alarms that the problem will worsen without rapid remedial action (UNEP/FAO/IPBES: www.unep.org; www.fao.org; IPBES 2018).

In a broad sense, soil conservation refers to the control of soil erosion and avoidance of soil degradation. Originally the term was synonymous with soil erosion control, the efforts for which were handled in isolation from other aspects of land management. Gradually, the concept of soil conservation evolved and attained the broader meaning that encompasses not only keeping the soil in its place but also maintaining or even enhancing its productivity. Today, soil conservation includes both the prevention of surface soil loss from erosion and the reduction of its productive capacity. Land degradation, which is the other major topic of this chapter, is defined variously but all definitions convey essentially the same idea: any change or disturbance to the land perceived to be deleterious or undesirable (see Section 18.4.1 for more explanations).

Soil conservation and (control of) land degradation are, indeed, very much intertwined. Although not synonymous, one cannot be considered in isolation from the other. However, soil (and land) degradation implies a much larger land area than soil conservation does; and, soil erosion control (which used to be considered synonymous with soil conservation) is often viewed as a subset of land degradation control, but not vice-versa. Thus, soil conservation and land degradation control are "similar but different" terms and will be treated as two major sub-sections of this chapter.

18.2 Soil Conservation

Tree-based land-use systems, in general, are perceived as highly desirable in terms of protecting and conserving the soil and reducing land degradation, and the disastrous consequences of indiscriminate land clearing and deforestation are all too well known. Agroforestry systems involving deliberate integration of trees on farmlands in proper configurations are a natural fit for soil conservation and land-degradation control. Indeed, large-scale planting of trees as windbreaks was the winning strategy that was adopted to address the devastating wind erosion in the Great Plains of the USA in the 1930s (see Section 18.3). When soil conservation and agroforestry emerged as major land-management strategies in the tropics during the late 1900s, it was only natural that the two activities meshed together in many places. Thus, right from the early days of agroforestry development, the relevance and advantages of agroforestry for soil conservation had been recognized (Lundgren and Nair 1985; Young 1989). Being major segments of land management, considerable research and development efforts have been made and voluminous literature is available on the various aspects of the theme. As in the case of topics of other chapters in this section of the book such as soil organic matter and fertility (Chapter 16) and biological nitrogen fixation (Chapter 17), several comprehensive and highly-rated textbooks and other excellent resource materials are available on those details (causes, processes, mechanics, measurements, control measures, experiences, etc.), including Brady and Weil (14th edition, 2008); Moldenhauer and Hudson (1988); and Lal (1989). Therefore, in this book, the treatment of those aspects will be limited to their relevance, applicability, and special considerations for application to agroforestry with some explanations of the general principles and approaches to the extent deemed necessary for understanding the discussions.

18.3 Historical Developments in Soil Erosion

Soil erosion is caused primarily by water (water erosion) and wind (aeolic erosion); although it is also caused by gravitational force (in steeply sloping bare lands), ice (glaciers), and snow, those forms are not considered here. Soil erosion is said to have been a problem since time immemorial (Lal 1987), but the awareness about its seriousness and the need for soil conservation arose in the 1930s following a massive ecological disaster in the United States. The period of the Great Depression in the US (1929–1939) was marked by a devastating eight-year drought that started in 1931. A large area of the Great Plains (southwestern Kansas, Oklahoma panhandle, Texas panhandle, northeastern New Mexico, and southeastern Colorado) that was once known for its rich, fertile, prairie soil was ravaged by the drought. Cattle ranching, which was the main form of land use in the Plains, had been replaced by wheat farming leading to over-plowing the land and the removal of the grass that used to hold the soil against the erosive forces of the wind. With the onset of the long drought and devastating winds, the once productive region became a humongous "Dust Bowl" filled with enormous dust storms (Figure 18.1), each extending over hundreds of kilometers, destroying crops and making life there untenable; millions of people were forced to leave their homes, searching for work elsewhere. To address the serious problems caused by the Great Depression and massive dust storms, the US Congress passed the Soil Conservation Act, which was signed into law by President Theodore Roosevelt in 1935. A Soil Conservation Service (SCS) was established in April 1935 within the Department of Agriculture (USDA), and the federal government assumed the permanent responsibility for reducing water and wind erosion of the nation's soils. A massive tree-planting program was undertaken when two hundred million wind-breaking trees (red cedar, *Juniperus virginiana*, and green ash, *Fraxinus pennsylvanica*) were planted across the Great Plains, stretching from Canada to northern Texas, to protect the land from erosion. The re-plowing of the land extensively into furrows, planting trees in shelterbelts, and adopting the practice of crop rotations resulted in a 65% reduction in the amount of soil loss by wind erosion by 1938. The drought continued until the rains finally came in 1939 (Figure 18.2).

In 1994, following a major reorganization of the USDA, the SCS was renamed as the Natural Resources Conservation Service (NRCS) https://www.nrcs.usda.gov, to better reflect the broad scope of the agency's mission. In conjunction with the above developments in soil conservation in the US since the 1930s, soil conservation programs spread to other countries, and soil conservation became a part of agricultural policy in the tropics since the 1970s and the World Soil Charter was formulated (FAO 1982).

During the more than 80 years since the creation of the US SCS/NRCS and the end of the Great Depression, the concept of soil conservation has undergone significant changes. Originally soil conservation was synonymous with soil erosion control and the control efforts were

Figure 18.1 The 1930s' Dust Bowl in the USA. Source: https://www.bing.com/images/search?view=detailV2&id=7666C9E63FF22A48C8A2E96F5D8A204BBFA144E7&thid=OIP.7lD-yV4y7Re4aehIReG_LgHaE8&mediaurl=http%3A%2F%2Fwww.lastwordonnothing.com%2Fwp-content%2Fuploads%2F2014%2F04%2Fshutterstock-haboob-dust-storm.jpg&exph=3456&expw=5184&q=photos+of+dust+bowl&selectedindex=69&ajaxhist=0&vt=0&ccid=7lD%2ByV4y&simid=608014459377683463&sim=11

Figure 18.2 The Dust Bowl, the 1930s. Source: https://www.bing.com/images/search?view=detailV2&id=7666C9E63FF22A48C8A2E96F5D8A204BBFA144E7&thid=OIP.7lD-yV4y7Re4aehIReG_LgHaE8&mediaurl=http%3A%2F%2Fwww.lastwordonnothing.com%2Fwp-content%2Fuploads%2F2014%2F04%2Fshutterstock-haboob-dust-storm.jpg&exph=3456&expw=5184&q=photos+of+dust+bowl&selectedindex=69&ajaxhist=0&vt=0&ccid=7lD%2ByV4y&simid=608014459377683463&sim=11

handled mostly in isolation from other aspects of land management. During the 1970s, the term attained a broader meaning. As Young (1989) concluded based on an authoritative review on the role of agroforestry in soil conservation, “soil conservation being largely equal to the maintenance of soil fertility which requires control of erosion and maintenance of organic matter and physical properties, agroforestry practices that enhance these attributes are a logical choice for enhancing soil conservation.” Today, in the context of agroforestry, soil conservation encompasses both soil-erosion control and maintenance of soil fertility. Land (soil) degradation, on the other hand, is viewed as any change or disturbance to the land (soil) perceived to be deleterious or undesirable.

A large number of scientific publications that address soil erosion and conservation were published during the 1980s, including proceedings of prominent international conferences, multi-authored publications (e.g., Hamilton and King 1983; El-Swaify et al. 1985; Lal 1989), and journal papers. These publications reflect the emerging trends in soil-conservation research during the late 1990s. The salient aspects of these developments are listed below.

- Erosion is a major form of soil degradation
- Soil conservation should address not only erosion, but also other forms of physical, chemical, and biological deterioration of soil
- The adverse effects of erosion used to be expressed in terms of the reduction of crop yields and/or loss of soil. The loss of soil organic matter and plant nutrients, which leads to a serious decline in the ability of soil to sustain agricultural production, however, was seldom accounted for as a serious effect of soil erosion
- The traditional “barrier approach” to soil conservation (mechanically constructing physical structures to control runoff) involved excessive economic and labor costs and caused an irreparable loss of or damage to valuable topsoil. Gradually, the emphasis shifted to using soil cover as a means of controlling erosion, which brought agroforestry into focus in soil conservation programs
- Soil erosion may contribute significantly to global carbon emissions. The soil organic carbon redistributed over the landscape may be mineralized exposing the hitherto encapsulated C to microbial processes

18.4 Water Erosion

18.4.1 General Principles and Considerations

The mechanics: Soil erosion (caused by water) is a three-step process involving the detachment of the soil particles from the soil mass, transportation of the detached particles by moving water, and deposition of the transported soil somewhere away from its original place. The falling raindrops that hit the soil surface (at terminal velocities up to 30 km h^{-1}) detach the soil particles and send them flying in all directions splashing as much as 0.7 m vertically and 2.0 m horizontally, with very heavy rains causing splashing of as much as 225 t ha^{-1} of soil (Brady and Weil 2008). The detached soil particles are then transported by the runoff water down the slope and deposited at varying distances ranging from the lower elevations within the field to creeks, rivers, and oceans. The magnitude and seriousness of soil erosion caused by falling rain depend on a large number of site-specific and regional factors including the soil and vegetation characteristics and the frequency and severity of rainfall.

One of the important aspects of the process of water erosion that is quite relevant to agroforestry is the realization that the erosion is mostly initiated by the impact of the falling raindrop (that causes detachment of the soil particles) rather than the flow of the moving water. Soil conservation efforts in the past used to be focused on controlling the flow of water across the field rather than reducing the velocity and impact of falling raindrops before they hit the soil surface. Tree canopies, which provide a multi-layer defense against the impact of falling raindrops on soil particles, have special significance in this context. In agroforestry systems with different vertical strata of canopies, the velocity of raindrops that hit the soil surface directly could be significantly reduced by the upper (usually tree) canopies. The chances also exist, however, for smaller droplets from the upper canopies coalescing and hitting the ground and splashing the soil even after the rain ceases, but the impact of such events varies depending on site-specific conditions (see Section 18.3).

Types: Three different types of erosion are recognized depending on the nature of water flow on the soil surface and its effects during the erosion process: sheet, rill, and gully. **Sheet erosion** is the term for erosion that happens when the soil is detached and moved by a uniform and gentle sheet of water. The sheet of water usually gets transformed into tiny channels called rills depending on the contour and the presence of pebbles and other objects on the soil surface, and **rill erosion** sets in. When the rainfall intensity and duration increase, the water cuts deeper into the soil, forming gullies, causing **gully erosion.** The depth and severity of the gullies are, again, dependent on several local factors. Intense erosion over prolonged periods can transform the gullies into ravines – the ultimate stage of water erosion. Although gullies are more conspicuously visible than rills, the sheet erosion and rill erosion are responsible for more soil loss than gully erosion; while rills can usually be covered up by usual tillage operations, special efforts are needed to reclaim land severely impacted by gully erosion (Figures 18.3, 18.4, 18.5, and 18.6).

Major causative factors: The major factors affecting water erosion are related to rainfall, soil, topography, and soil cover, and land-use

Figure 18.3 Rill and gully erosion. Tiny channels called rills are formed at first, as at the top of the picture. Then, depending on the contour and the presence of pebbles and other objects on the soil surface, **rill erosion** sets in. When the rainfall intensity and duration increase, the water cuts deeper into the soil and the rills coalesce forming gullies, resulting in **gully erosion** as at the bottom of the picture. (Photo Courtesy: G. Budowski, CATIE, Costa Rica, 1984)

Figure 18.4 Gully erosion. (Photo: USDA Natural Resources Conservation Service)

Figure 18.5 Gully erosion leading to the formation of ravines. The depth and severity of the gullies are dependent on several local factors. Intense erosion over prolonged periods can transform the gullies into ravines – the ultimate stage of water erosion (Figure 18.6). (Photo Courtesy: G. Budowski, CATIE, Costa Rica, 1984)

Figure 18.6 The Chambal Ravines in Madhya Pradesh, India. (Photo: Amita Sharma and A. Arunachalam)

management practices. These factors are included in the measurement of soil erosion described in the following subsection.

18.4.2 Measurement of Soil Erosion by Water

The rates and quantities of soil erosion are usually estimated based on some predictive models because of the difficulties in measuring the soil lost by erosion. Mathematical equations have been developed linking several easily measurable or otherwise available factors with soil erosion; these equations are then calibrated using measurements from standardized plots. The most widely used equation (predictive model) is ***The Universal Soil Loss Equation (USLE)*** that has been developed by the USDA based on a large amount of experimental data (Wischmeier 1976; Wischmeier and Smith 1978). The model can be calibrated for a given region to predict erosion losses from experimental plots, which are then extrapolated to farmland under similar treatments.

The USLE states: $\mathbf{A = R \times K \times LS \times C \times P}$ where,

A = soil loss t ha^{-1} yr^{-1}
R = the *rainfall factor* (ca ½ mean annual rainfall in mm)
K = the *soil erodibility factor* (range: 0-1)
L = the *slope length factor*
S = the *slope steepness factor*
C = the *cover factor* (range: 0-1), and
P = the *support practice factor*.

As can be seen, the equation involves one rain-related factor (R), three soil-related factors (K, L, S), and two land-management factors (C, P). Calculation of the rainfall factor (R) requires detailed information on the rainfall intensity of the study site. However, for practical purposes, half the total annual rainfall in mm is taken as a good approximation of the R factor in the tropics. Thus, the R factor for a rainforest site with 2000 mm annual rainfall is 1000, and for a savanna site with 600 mm, it is about 300. The soil erodibility factor (K) denotes the resistance of soil to erosion. In a hypothetical situation where the soil is totally resistant to erosion, K = 0; on the other extreme, K = 1. The K value for a given soil is determined by experiment, such that the product R * K gives soil loss rate on bare soil in a standard erosion plot (22 m long, with a uniform slope of 9% or a slope angle of 5.14°). Typical K values are 0.1 for more resistant soils such as Oxisols with stable aggregates and 0.5 for highly erodible soils. The slope-length factor (L) and slope steepness factor (S) give the respective ratios of soil losses from the study site of similar length and slope as the standard USLE plot; these factors are usually expressed as a combined factor, the *topographic factor* (LS). "Standard" values of LS factors for different sites with varying lengths and steepness are available. The cover factor (C) is the ratio of soil loss from a specified crop cover and management to that from bare fallow; for bare fallow, C = 1; for fields with total cover throughout the year, it is close to 0; a full range of values in between these extremes is expected for soils under varying cover intensities. The support practice factor (P) indicates the ratio of soil loss from a plot with a given conservation practice to that with crops grown under no conservation (most-erosion causing) practices, such as planting rows along the slope. The values range from 0 to 1; values of 0.3 to 0.4 are common in usual agricultural fields when the slopes are left as they are (with no special conservation practices).

The USLE has been used widely since the 1970s. The equation was subsequently revised and computerized to what is called the **Revised Universal Soil Loss Equation (RUSLE)** (Renard et al. 1977). The RUSLE, which has the same basic features as the USLE, is a computer software package and is constantly being revised and refined based on experience gained from around the world. Although developed for the typical monocultural cereal fields of the US, the model has been used widely, including in tropical conditions. However, as expected, many of the assumptions on which the model is based are not fully applicable in the tropics, leading to unrealistically high values, especially in areas with high rainfall and steep slopes. To overcome this difficulty, several modifications have been proposed. Thus, several variants of USLE/RUSLE are in use under different conditions.

A major feature of these predictive models is that they indicate the very high potential for reducing soil erosion through management, most importantly by providing effective land cover. The rainfall erosivity (R) and, to some extent, soil erodibility (K), are characteristic of the site, with little possibility for change by human intervention. However, K values can change in response to soil management: for example, if the organic matter content falls by 1%, the K factor will rise by about 0.04 units. Slope length and angle can easily be manipulated by conservation measures. For example, contour terraces created using earth-moving machinery (Figure 18.7) used to be the main approach to soil conservation in the 1960s and 1970s. The cost of not only creating the terraces but also maintaining them over the years was, however, too high. Moreover, the "cut-and-fill" procedure of terrace construction was too damaging from the soil-fertility standpoint. Such mechanical terraces were later replaced by biological contour terraces in which barriers (grass strips, hedges, terraces, bunds, and cut-off ditches) would be established across the slopes along the contour to reduce slope length and steepness. A schematic presentation of this concept is given in Figure 18.8 and two field examples are presented as Figures 18.9, 18.10, and 18.11). An important factor that has a dramatic effect on erosion-control and is highly relevant to agroforestry is the cover factor. Tree crops with cover crops beneath can reduce erosion considerably (0.1 to 0.01 of its rates on bare soil). Crop-residue management, i.e., whether (or not) residues are applied as a surface mulch is also critically important.

The lack of easy and cost-effective methods of measuring soil erosion rates under field conditions has remained a major problem in soil conservation and management, especially under resource-limited tropical conditions. The methods such as using collection tanks (Hudson 1993) are expensive in terms of equipment and personnel, and budget restrictions tend to reduce the period and area of analysis. The USLE plot method,

Figure 18.7 Contour terraces – The engineering approach to soil conservation. (Source: PKR Nair 1984)

which is the standard way for estimating erosion data at field level using an erosion plot (Figures 18.12 and 18.13) 22 m long, with a uniform slope of 9% or a slope angle of 5.14°, is difficult to set up and monitor precisely. In real-world conditions, it could be difficult to find multiple plots of such exacting standards that would be needed for setting up a research study. Several other problems also need to be addressed under field conditions. For example, during heavy rains, the water flow down the slope becomes excessive such that toward the low end of the plot, there could be lateral spill-over of water to adjacent plots over the metallic (tin) or other barriers that are used to separate the plots. Another problem is that during heavy rain events the collection tanks get filled up fast and emptying them would be difficult especially at nights. To address this, mechanical devices such as "tipping buckets with counters" have been devised such that when the buckets (or small containers) at the down end of the plots get filled up, they are automatically emptied and a counter will record the number of times such events occur within a defined period, say 24 hours. The problem with this method is that the soil that is carried by water in such buckets that are emptied will remain unrecorded. Lack of uniformity of site conditions is an important issue associated with the experimental set-up. Furthermore, rainfall patterns are erratic from year to year and experimental resources may be limited to extend the studies over longer periods needed to average out such seasonal variations as has been the case of the few studies reported during the early years of agroforestry research (Lal 1989; Omoro and Nair 1993). In any case, under practical conditions, some erosion is unavoidable (Stroosnijder 2005).

18.4.3 Effect of Agroforestry Systems on USLE Soil Erosion Factors

Rainfall Erosivity: Erosivity, the rainfall factor (R) of USLE, is usually expressed as the EI_{30} index, which is the product of the energy of the storms multiplied by their maximum 30-minute intensity for all storms of more than 12.5 mm. The widely held assumption that agroforestry systems can reduce the rainfall erosivity (Section 18.3) may not be true in all agroforestry situations. The kinetic energy of falling raindrops

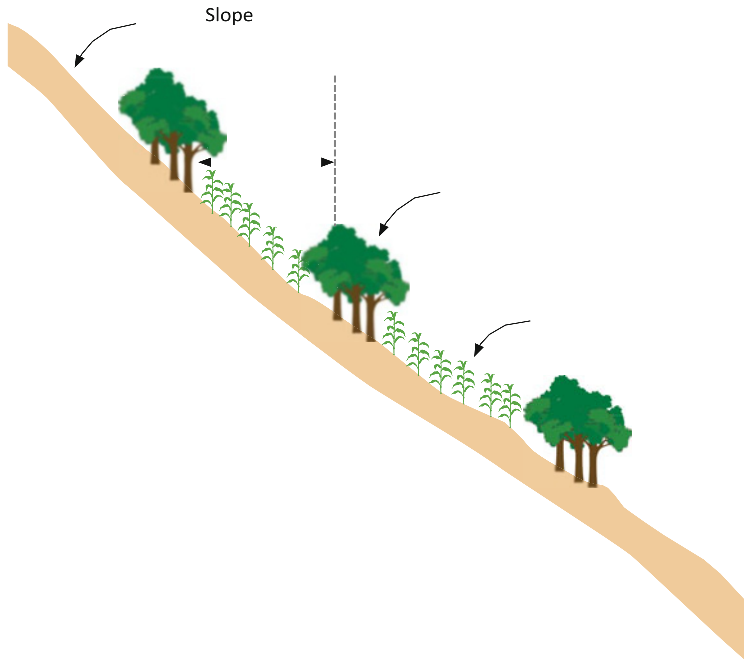

Figure 18.8 Schematic drawings of contour live hedges. The crop is grown in the alleys of multipurpose trees planted as hedgerows along the contour across the slope (see Figures 18.10 and 18.11)

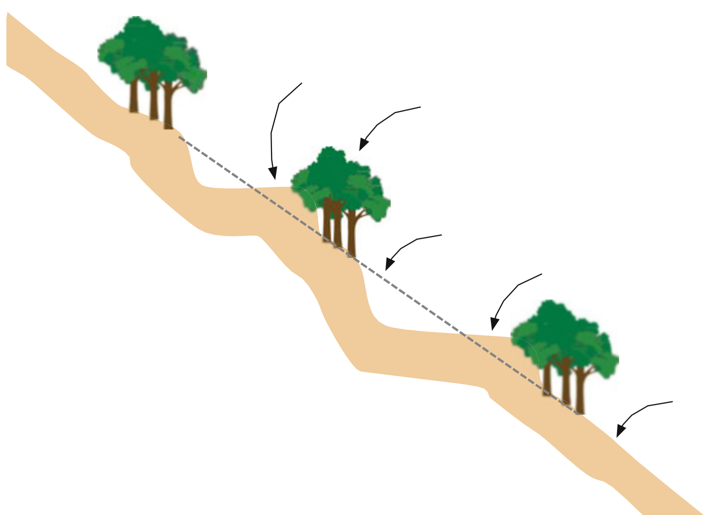

Figure 18.9 Schematic drawings of contour live hedges. Gradually, there will be natural terrace formation between the hedgerow lines. The dotted line indicates the original soil surface

Figure 18.10 Contour live hedges – Field Example 1: Hedgerows of *Leucaena leucocephala* in a field of cowpea (*Vigna unguiculata*), IITA, Nigeria. (Photo: Dr. BT Kang - deceased)

Figure 18.11 Contour live hedges of *Leucaena leucocephala* (in the Philippines) facilitate terrace formation when the soil that moves down with water is retained behind the hedges. (Source: Nair 1984)

Figure 18.12 Field measurement of soil erosion in an alley-cropping field of maize and *Leucaena leucocephala* in a gently slopping (~ 10% slope) land in Machakos, Kenya. (Photo: PKR Nair 1991)

Figure 18.13 Another field of the same study as in Figure 18.12 with Se*nna siamea* instead of *L. leucocephala* as the hedgerow species, in Machakos, Kenya. (Photo: PKR Nair 1991)

can be enhanced by the presence of a high, broad-leaved canopy. Raindrops coalesce into larger drops, which, while falling from a high (ca. 30 m) canopy, can attain a high velocity and cause severe splash erosion by the impact of the raindrops as reported under teak (*Tectona grandis*) plantations in Indonesia (Soemarwoto 1987). This phenomenon could be unique to tall-growing trees with very broad leaves such as teak but may not apply to low and dense canopied trees. Under alley cropping, although the canopy is low, it is not directly above the "cropped" land, but field measurements from such agroforestry systems have not been reported. Thus, although it is plausible that well-managed agroforestry systems may reduce overall erosion losses, the extent to which such reductions are caused by the reduction of rainfall erosivity is not fully known.

Soil Erodibility*:* The major influence of agroforestry practices on the soil erodibility (K) factor is through the effect on soil physical properties, mediated by soil organic matter. It is widely recognized that soil structure is of a higher grade under forest than under cultivation; this includes increased stability, lower detachability, and higher infiltration capacity. Under shifting cultivation, organic matter decreases and erodibility increases during the cropping period. Under the taungya system, there is usually a decrease in organic-matter content and infiltration capacity and higher erosion during the cropping period as compared to a young forest plantation without intercrops. Alley cropping and improved fallows have the potential to maintain SOM (see Chapter 16), in contrast to the almost invariable decline under sole cropping. In a field study at Ibadan, Nigeria, the topsoil organic carbon was 1.1% after six years of maize-leucaena alley cropping with leucaena prunings returned to the soil compared with 0.65% when leucaena prunings were removed (Kang et al. 1985). Unfortunately, recent studies of this nature have not been reported.

Reduction of Runoff*:* This is based on the barrier approach to erosion control, in which runoff and soil loss are checked utilizing barriers. Where trees are planted on soil-conservation works, including grass strips, bunds, and terraces, runoff and erosion are reduced; no specific additional effect, however, can be attributed to the presence of trees other than the indirect benefit from increased soil organic matter content associated with trees. Barrier hedges such as in alley cropping are effective in limiting runoff (Figures 18.9, 18.10, and 18.11).

The Ground Surface Cover*:* Soil cover formed of living and dead plant material including herbaceous plants and perennial cover crops, crop residues, and tree litter and prunings can effectively check raindrop impact and runoff, and the potential of this "cover approach" for reducing erosion is greater than that of the "barrier approach" discussed above. Agroforestry can contribute to the maintenance of such effective ground covers for longer periods in several ways.

18.4.4 Agronomic Approaches to Water Erosion Control

Land preparation for sowing or planting a crop involving extensive soil tillage and "clean cultivation" that leaves the soil bare, with a fine tilth used to be the conventional agronomic practice the world over, and it continues to be so even today in many places. The continuation of this traditional practice has been challenged since the 1970s with the evolution of the concept of **reduced or minimum tillage** in conjunction with the use of chemical herbicides instead of mechanical means for weed control and the development of appropriate machinery to help plant the seeds even when the soil is covered by crop residues (Figure 18.14). Many mechanized operations adopted such farming practices that reduced the time and cost of land preparation, which also had the added advantage of reducing the soil-erosion hazard by retaining plant residues on the soil surface rather than leaving it bare as in the traditional practice. Moreover, reduced tillage systems resulted in equal or even higher crop yields compared to traditional methods of land preparation. These encouraging trends led to the development and farmer adoption of several variants of the practice such as zero- or no-tillage,

Figure 18.14 No-till corn production systems in Wisconsin, USA. Leaving the crop residues on soil surface helps improve soil structure and reduce soil erosion. Source: http://corn.agronomy.wisc.edu/Management/L007.aspx

reduced tillage, ridge tillage, and stubble mulching that are collectively called **conservation tillage systems or conservation agriculture.** Conservation Agriculture (CA) is a philosophy of sustainable farming that can prevent losses of arable land and regenerate degraded lands. The three cardinal principles upon which it is based are 1. maintenance of a permanent soil cover by crops and/or through plant residue management, 2. minimum tillage which ensures least soil disturbance, and 3. crop diversification (Hobbs et al. 2007). Agronomic literature is replete with numerous studies on various aspects of various conservation tillage and other conservation agriculture practices in a variety of conditions and cropping systems. As the adoption of conservation tillage practices progressed, the practices have been modified by integrating them with the use of permanent vegetative barriers for soil conservation. For example, the integration of narrow rows of permanent vegetation, usually perennial grasses and low-growing shrubs, as erosion-control measures has been a time-tested practice on sloping lands, especially in developing countries. The combination of the practices of conservation tillage and vegetative barriers as soil conservation measures led to the revival and increasing use of some agroforestry practices such as contour planting of multipurpose (fodder and fruit) trees that have been long practiced in the sloping lands of the tropics.

Soil conservation, which used to be considered synonymous with soil-erosion control as mentioned before, became an important component of agricultural development programs in the tropics since about the 1970s. Some development agencies, notably of the Nordic countries (SIDA: Swedish International Development Agency, and NORAD: Norwegian Agency for Development Cooperation), in cooperation with international agencies such as the FAO and the World Bank, supported numerous soil conservation projects in Africa, Asia, and Latin America and the Caribbean regions, and valuable lessons have been learned from these efforts. Numerous reports that are available on these experiences provide a quick glimpse of the evolution of the concepts and methods of soil conservation. It is interesting, for example, how the barrier approach to soil conservation emerged over the years. As mentioned earlier (Section 18.4.2), the emphasis used to be on installing mechanical structures and barriers such as concrete and stonewall terraces, often designed by and installed under the directives of engineers with little background or consideration of biological properties of the soil. In the process of creating contour terraces, large volumes of topsoil would be cut and removed from an area extending over half the width of the terrace and filled over the other half of the area to level off (the so-called "cut-and-fill" method) and avoid any slope gradient in the terraced area used for cropping (Figure 18.7). The seriousness of the loss of valuable topsoil that would be removed and the problem in opening up the subsurface soil for cropping in the area from where the topsoil had been removed were seldom realized then. Gradually, such objectionable methods of mechanical terrace construction for soil conservation were replaced by biologically sound agroforestry terracing practices (Pelleck 1992), whereby perennial grasses, shrubs, fruit trees, and fodder trees would be used for terrace stabilization (Figure 18.11).

A related topic that merits mention in this context is the **Land Capability Classification** devised in the late 1950s by the USDA (Klingebiel and Montgomery 1961) as a basis for land-use planning and for identification of management practices that can minimize water-induced soil-erosion. The system was later adopted by several other countries as well. The overall approach is to suggest desirable land-use systems and the intensity of land use for various lands depending on their susceptibility to erosion, which in turn, is determined by various soil and climatic factors. Soils are classified into eight land capability classes, Classes 1 to VIII. Generally, land classes from I to IV are suitable for arable use, and Classes V to VIII are unsuitable for arable use due to erosion hazards; it is recommended that these lands (Classes V to VIII) should be used for grazing, forestry, or recreation and conservation. This concept, however, could not be applied under conditions of high population pressure, where cultivation extends into land classified as unsuitable for cultivation.

18.5 Wind Erosion

Wind erosion, or soil erosion caused by wind, is a major, worldwide problem mainly in arid and semiarid lands, but also some parts of the humid regions. Geographically, the major regions that are seriously impacted by wind erosion include sub-Saharan Africa, South and Central Asia, western parts of China, and the Great Plains of the US. In many of these regions, wind erosion causes more damages to crops and soils than water erosion. For example, in the six Great Plains states of the USA, the estimated annual soil loss by wind erosion from croplands, averaging 4 t ha^{-1} in Nebraska to 29 t ha^{-1} in New Mexico, exceeds soil loss by water erosion. The havoc caused by the Dust Bowl of the US during the mid-1930s has been described in Section 18.3.

18.5.1 Wind Erosion: Nature and Measurement

The mechanics of wind erosion are somewhat similar to those of water erosion, consisting of three processes: detachment, transportation, and deposition of soil particles. The abrasive power of the moving air to force detachment of the soil particles from the soil mass increases considerably when it is laden with already detached soil particles. Once detached, the soil particles go through a series of short bounces, called "saltation," along the soil surface, followed by a so-called "creep" by which they roll and slide along the surface of larger particles, and then they get transported in "suspension" and move parallel to the ground for kilometers and upward to several meters in the turbulent action of the wind, until the wind subsides or precipitation washes the particles down. The major factors affecting wind erosion include wind velocity and turbulence, surface roughness, and various soil properties.

Similar to the USLE for predicting the water erosion, there is a **wind erosion prediction equation (WEQ)**, whereby the predicted wind erosion is a function of several factors:

$$E = f(I \times C \times K \times L \times V)$$

E = Predicted wind erosion
I = Soil erodibility factor
C = Climate factor
K = Soil-ridge-roughness factor
L = Width of field factor
V = Vegetative cover factor

Similar to the RUSLE, a **revised wind erosion equation (RWEQ)** has also been developed.

The factors included in the WEQ and RWEQ suggest some methods for reducing wind erosion. Some of the factors, however, are difficult to be maintained in areas prone to serious wind erosion. For example, the vegetative cover factor: usually wind erosion is common in dry (arid and semi-arid) regions and is severe during the dry period when it is difficult to maintain vegetative cover on land. Nevertheless, some of the conservation tillage practices (Section 18.4.4) such as stubble mulch farming might be advantageous in such situations. The importance of maintaining vegetation cover to the extent possible in reducing wind erosion has been well recognized. As mentioned in Section 18.3, the massive tree-planting program by which two hundred million wind-breaking trees were planted in conjunction with other soil conservation programs during the period of the Great Depression resulted in a 65% reduction in the amount of soil loss by the wind across the Great Plains of the USA.

18.5.2 Windbreaks and Shelterbelts (in the Tropics)

The use of trees on farms as windbreaks and shelterbelts as barriers to reduce wind speed and protect crops and soils is one of the major agroforestry practices in the temperate regions of the world as described in Chapter 10 (Section 10.3.3). The term “shelterbelt” represents a type of windbreak, consisting of long, multiple rows of trees and shrubs around farms (as opposed to windbreaks that may also be along plot boundaries within a farm), or along seacoasts to protect agricultural fields from damage by wind and/or inundation by tidal waves as the case may be. Over the years, the two terms (windbreaks and shelterbelts) are used almost synonymously to refer to barriers of trees and shrubs used to reduce wind speed on farms (Brandle et al. 2009) and reduce the impact of tidal waves. Historically, the practice has special relevance to North America, where it was adopted successfully on a large scale to address the havoc caused by the severe wind erosion (the Dust Bowl) in the Great Plains in the US during the period of the Great Depression as described at the beginning of this chapter (Section 18.2). Shelterbelts have also been used for a long time in several places, most notably on the Bay of Bengal coast of India and Bangladesh. The temperate-zone windbreaks have been discussed in Chapter 10 (Section 10.3.3). The description below is focused primarily on windbreak systems in the tropics.

Throughout the African continent, farmers use windbreaks to protect crops, water sources, soils, and settlements on plains and gently rolling farmlands. Hedgerows of *Euphorbia tirucalli* protect maize fields and settlements in the dry savannas of Tanzania and Kenya. Tall rows of *Casuarina* line thousands of canals and irrigated fields in Egypt. In Chad and Niger, multi-species shelterbelts protect vast expanses of cropland from desertification (see Section 18.6.1). The practice is not new, although the design of multipurpose windbreaks for smallholders will require new inputs from agroforestry practitioners.

Structure of Windbreaks. Windbreaks usually consist of multistory strips of trees and shrubs planted preferably three rows deep on the windward side of the land to be protected and are most effective when oriented at right angles to the prevailing wind direction. While their length and height may vary dramatically, it is common in the dry savannas of Africa to plant windbreaks 100 m long or more, with a peak height of 10 m. Small living fences and hedgerows can also act as windbreaks for small sites such as homegardens and nurseries. Windbreaks, however, are distinguished from boundary plantings and living fences by their orientation (facing the wind), and by their multistory, semipermeable design (Figure 18.15). Very dense windbreaks may do more harm than good since they will tend to create strong turbulence that will scour the soil on the windward side and damage crops on the leeward side. Conversely, gaps in the trees will channel the wind, increasing the velocity on the leeward side and promoting soil erosion and damaging crops.

The protected zone created by windbreaks is defined as the area on both leeward and windward sides where wind speed is reduced by 20% below incident wind speed. The effective distance of protection is expressed as multiples of the height (H) of the tallest rows of trees. Practical windbreak effects extend to a distance of 2–5 H windward of the windbreak (the direction from which

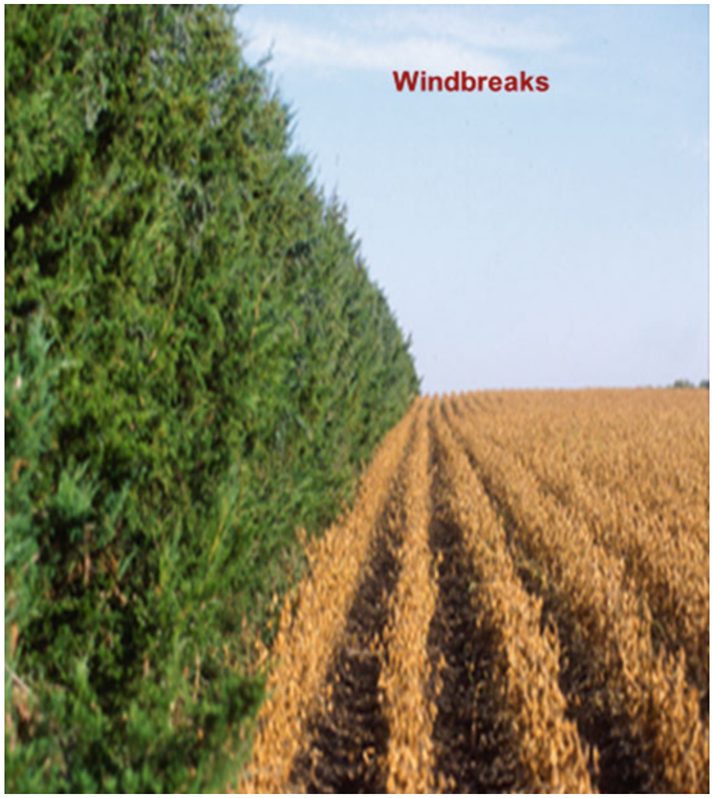

Figure 18.15 Windbreak in a corn (*Zea mays*) field in Nebraska, USA
Source: USDA/National Agroforestry Center
See Chapter 10, Section 10.3.3, for descriptions and photos of windbreaks in the temperate zone (North America), including a schematic presentation of a multifunctional windbreak (Figure 10.7)

the wind is coming) and 15–20 H leeward (direction downward from the windbreak), but usually, a common calculation of the extent of the protected area is 10 H leeward. This means if the trees are 10 m tall, crops up to 100 m in the leeward direction could be protected. The protective influence will diminish with increasing distance from the windbreak. A permeable windbreak will shelter a longer stretch of cropland than a dense windbreak. The most effective windbreaks provide a semi-permeable barrier to wind over their full height, from the ground to the crowns of the tallest trees. An "ideal" windbreak should consist of a central core of a double-row planting of fast- and tall-growing species such as *Eucalyptus* spp., *Casuarina* spp., and neem (*Azadirachta indica*), and two rows each of shorter spreading species such as *Senna* (syn. *Cassia*) spp., *Prosopis* spp., and *Leucaena* spp. On both sides of the central core. *Agave* spp. are also used, especially on the outer rows (away from crop fields). Since the trees change their shapes as they grow, it is usually necessary to mix several species of different growth rates, shapes, and sizes in multiple rows. Some fast-growing species should be used to establish the desired effect as rapidly as possible. Fast- and slow-growing species, as well as trees with longer and shorter lifespans, should thus be mixed to extend the useful life of the windbreak. The mixing of species also protects against attacks from diseases or insects that can easily destroy stands of a single species. Species diversity of windbreaks can also bring a wider variety of useful products to local users. A fully developed windbreak can yield wood, fruit, fodder, fiber, and honey for sale and home use. Where animals are allowed to graze nearby, at least some of the lower, outer trees or shrubs should be relatively unpalatable, while fodder species may fit closer in to the center or along an inside edge where they are not exposed to animals, but can be cut by hand.

Neem has been successfully used in Niger; its unpalatable leaves protect it from livestock damage.

Although some trees such as neem, *Casuarina* spp., and *Eucalyptus* spp. are widely used in windbreaks, they should be used selectively. *Eucalyptus* should not be used alone as it has a sparse understory and may negatively affect water availability and crop productivity in the vicinity. Neem is known to shade crops and thus reduce the land available for crop production. On the other hand, people have constructed successful windbreaks with such unlikely trees as cashew (*Anacardium occidentale*) and local *Acacia* spp. The species selected must fit together as a group into a larger overall design that, in turn, complements the local landscape and land-use system. While species diversity is important, there are constraints on species choice both for indigenous and exotic species. Environmental hazards such as insect pests (especially termites), wild and domestic animals, poor soil, and drought, will narrow the choice as well as reduce the tree's growth rate. Water management, especially during establishment, will be important, as in any attempt to establish trees in a dry environment.

Anticipated Benefits of Windbreaks. The protective and productive benefits of windbreaks at a given site should be weighed against the costs before proceeding with detailed plans and planting. Aside from the direct costs for labor and planting material, windbreaks will take some land out of crop production, and will compete for water, light, and nutrients. Increased crop yields, soil improvements, and by-products must be sufficient (in the tropics) to cover these costs and still produce a net benefit. Although very little information is available on the quantities of wood (as fuelwood, poles, or other products) from trees growing in windbreaks, some available preliminary results are encouraging. The reported effects of windbreaks on crop yields vary considerably. In some cases, grain yields have increased significantly; in other cases, the effects have been unfavorable due to competition for water and light, the land area "lost" to the planted trees, and the changed microclimate.

18.5.3 Soil Erosion Rates Under Agroforestry Systems

Reports on recorded rates of soil erosion under agroforestry systems are scanty. A major problem is the paucity of a reliable and easy method for measuring erosion (Section 18.4.2). Moreover, erosion rates are often reported using imprecise terms such as "tolerable" and "acceptable." Early records of the extent of soil erosion under some agroforestry and other land-use practices include those reported by Wiersum (1984). Further, Lal (1989) reported some results of erosion studies in alley cropping at IITA (International Institute of Tropical Agriculture). These may, however, be viewed in the light of the above general deficiencies of such datasets. In a recent meta-analysis based on published studies from sub-Saharan Africa of the ecosystem benefits including soil-erosion control provided by agroforestry practices, Kuyah et al. (2019) noted that agroforestry practices reduced runoff and soil loss and improved infiltration rates and soil moisture content. The authors were concerned, however, that the erosion studies available and included in the study were too few and inadequate to draw valid conclusions.

The NRCS/Soil Conservation Service (USA) sets limits of tolerable erosion in the range of 2.2 – 11.2 t ha^{-1} yr^{-1} (lower figures for shallow soils over hard rock and higher figures for deep soils). These limits are based on two notions: first, erosion is acceptable up to the rate at which soil is renewed by natural processes, and secondly, these rates are assumed to be practicable under common farming conditions. Arguing that tolerance limits for soil erosion "should be set based on sustained crop yields translated into terms of maintenance of organic matter and nutrients," Young (1989) proposed that erosion rates under tropical agroforestry systems could be classified as low (< 2 t ha^{-1} yr^{-1}), moderate (2 – 10 t ha^{-1} yr^{-1}), and high (> 10 t ha^{-1} yr^{-1}), and the erosion potential of some common tree-based systems may be summarized as follows:

Land-use systems with low erosion rates: Natural rain forest, Forest fallow in shifting cultivation, Multistory tree gardens, Most undisturbed forest plantations, Tree plantation crops with cover crop and/or mulch

Land-use systems with moderate to high erosion rates: Cropping period in shifting cultivation, Forest plantations with litter removed or burned

The large range of values for systems that have high erosion potential indicates the importance of management practices rather than the intrinsic properties of the systems. Trees do not necessarily lead to control of erosion. What matters is how agroforestry systems are conceived and managed; when designing tree fallow and agroforestry systems for erosion control, the primary aim should be to establish and maintain a ground cover of plant litter, which will also help maintain soil organic matter, and hence of soil physical properties and erosion resistance. The importance of maintaining crop residues and the litter layer than tree-shade cover in controlling erosion has been well known for a long time (Elwell and Stocking 1976) and validated time and again in different places. For example, Sepulveda and Carrillo (2015) studying soil erosion in a coffee agroforestry system (*Coffea arabica* under a mixed shade of *Inga* spp. and *Musa* spp.) in northern Nicaragua found that the litter layer and the slope gradient were the principal erodibility factors, of which the former accounted for 66% of the variability of erosion compared to only 4% by the slope gradient.

In summary, by far the greatest effect in reducing erosion can be achieved by maintaining a ground surface cover of litter. Among tropical agroforestry practices, multistory tree gardens and shaded perennial systems are always likely to control erosion, but even this may not be true for a farmer with a passion for clearing away all plant residues.

18.6 Land Degradation

18.6.1 Definitions and Characteristics of Land Degradation

As mentioned at the beginning of this chapter (Section 18.2), land degradation is defined variously, but all definitions encompass the same or similar meaning: "any change or disturbance to the land perceived to be deleterious or undesirable" (Johnson et al. 1997). The journal *Land Degradation & Development* (https://onlinelibrary.wiley.com/page/journal/) defines land degradation as "the loss of utility or potential utility through the reduction of or damage to physical, social, cultural, or economic features, and/or reduction of ecosystem diversity." Wikipedia defines it as "a process in which the value of the biophysical environment is affected by a combination of human-induced processes acting upon the land. It is viewed as any change or disturbance to the land perceived to be deleterious or undesirable." Several other definitions also have been proposed, and numerous illustrations are available. Some field examples of the various forms of land degradation are presented in Figures 18.16 and 18.17.

The multiplicity of definitions indicates that land degradation represents a concept, which cannot be embodied accurately in an abstract definition. That concept is that it refers to the loss of actual or potential productivity and utility of land and the decline in its quality and the inherent capacity to produce economic goods and perform functions of environmental moderation (Eswaran et al. 2001; Nair et al. 2011). Information on the cause-effect relationship linking land degradation to quantity and quality of land productivity is scanty. That is not surprising, because it is difficult – even unrealistic – to consider the physical, chemical, and biological processes in isolation from one another. This complex nature of land degradation makes it difficult to define it in quantitative terms and establish a cause-effect relationship linking it to agricultural/forestry production (Eswaran et al. 2001). Soil degradation, which is a subset of land degradation, is used in a

Figure 18.16 An eroded land in Mwingi, Kenya. (Photo: ICRAF/World Agroforestry)

Figure 18.17 Another form of land degradation. Source: Bobby Gill bgill@savory.global. c/o: sequestering-carbon-in-soil-addressing-the-climate-threat@googlegroups.com

limited sense to include the physical, chemical, and biological decline in soil quality.

Desertification is a major form of land degradation in the arid, semiarid, and subhumid regions of the world. The UNCCD (United Nations Convention to Combat Desertification), established in 1994, defines it as "land degradation in arid, semi-arid, and dry sub-humid regions resulting from various factors, including climatic variations and human activities" (www.unccd.int/

convention/about-convention). It is an outcome of the interplay between natural processes and anthropogenic factors that involves processes and patterns over a range of temporal and spatial scales. The common visible impact is dryland degradation that appears as vegetation degradation, water and wind erosion, and chemical and physical deterioration of soil properties. Desertification is threatening the livelihoods of approximately one billion people in over 100 countries, and each year 12 million hectares of arable lands are lost to drought (https://www.unccd.int/). Recognizing the urgency of halting and reversing land degradation in the dry areas, the UNCCD proposed in 2015 the need to attain land degradation neutrality (LDN) by 2030, which has been recognized as one of the UN Sustainable Development Goals (UN SDG: see Chapter 23, Annexure I). At the heart of LDN are improved land management practices and better land-use planning to improve economic, social, and ecological sustainability for present and future generations. Agroforestry is one of the prominent such practices.

18.6.2 The Nature and Extent of Land Degradation

As mentioned in Section 18.2, it is difficult to grasp the seriousness of land degradation in its totality. Numerous reports of studies commissioned by various UN agencies and other entities are available describing the nature and extent of land degradation. The Land Degradation and Restoration Report, 2018, of the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) is a comprehensive and recent one. It recognizes land degradation as "a pervasive, systemic phenomenon occurring in all parts of the world," which affects about 3.2 billion people, and signifies a monetary cost of 10% of annual gross product globally (IPBES 2018). The productive capacity of the land cannot, however, be assessed by any single measure. Therefore, indicators or variables that are often functionally not related to the process they are supposed to "indicate" are used. These indicators might just be correlates that may show that land degradation has taken place but not measures of the actual degradation. For example, the accumulation of sediment against a down-slope barrier may indicate that land degradation is occurring upslope, or a decline in crop yields may indicate that soil quality has changed and soil (land) degradation is occurring. Since the soil integrates a variety of important processes involving vegetation growth, the overland flow of water, infiltration, land use, and land management, its condition is one of the best indicators of land degradation. Thus, pieces of evidence from the soil and plants, growing on it – that are indicators of soil degradation and soil productivity, respectively – are considered major indicators of land degradation.

Physical, chemical, and biological processes and factors are involved in causing or exacerbating land degradation. Visible signs of physical degradation include crusting, compaction, accelerated water runoff, and soil erosion that are is set in motion by the deterioration and breakdown of soil structure. Factors and conditions that contribute to physical degradation include excessive cultivation and use of heavy machinery, overgrazing and trampling by animals, and removal of plant cover over soils such as in deforestation. Chemical degradation includes processes such as acidification, leaching, salinization, and decrease in cation retention capacity, all of which collectively lead to soil-fertility depletion. Acidification caused by leaching and depletion of bases such as calcium and magnesium is the common form of chemical degradation in high-rainfall areas, whereas salinization and excessive build-up of salts in crop root-zones that are often caused by poor irrigation management is the major form of chemical degradation in arid and semiarid regions. The biological effects of land degradation include the decline in land biodiversity and reduction in total and biomass carbon and are related to eutrophication of surface water, contamination of groundwater, and emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from terrestrial/aquatic ecosystems to the atmosphere. The major causes and processes involved in land degradation and the common analytical procedures to detect them are summarized in Table 18.1 (adapted from Nair et al. 2011).

Because of the different definitions and terminology, large variation exists in the available statistics on the extent and rate of land degradation. The UNEP Global Assessment of Human-Induced Soil Degradation (GLASOD) in the early 1990s identified areas where "human intervention [had resulted] in a decreased current and/or future capacity of the soil to support life, based on expert opinion" (Oldeman et al. 1991). According to them, human-induced soil degradation affected 1,964 million hectares of land globally (i.e., 15% of the terrestrial land), mainly due to water erosion with 2% of the soils were extremely or strongly degraded (Table 18.2). Dregne and Chou (1994) estimated that the degraded lands in dry areas amount to 3.6 billion ha or 70% of the total land areas in these regions. The principal difference between the two estimates is the status of vegetation. Although the estimates cover only dry areas, they also include the status of vegetation on the rangeland. Gibbs and Salmon (2015) reviewed the major databases and methodologies used to estimate the area of degraded land and reported that "global estimates of the total degraded area vary from less than 1 billion ha to over 6 billion ha, with equally wide disagreement

Table 18.1 Major types of land degradation: Indicators and measurement

Type of degradation and extent of area globally		Description	Indicators / Measurement	
Physical degradation	Water erosion (749 M ha)	• Removal of soil particles, usually of finer/fertile soil fractions • Sheet-, rill-, or gully erosion	Soil loss (USLE and RUSLE)	
	Wind erosion (280 M ha)	• Removal of soil by wind • Usually sheet erosion	Soil loss (Wind erosion equation)	
	Soil compaction	Breakdown of soil structure caused by use of heavy machinery	Soil porosity	
			Aggregate stability	
	Waterlogging	Caused by a rise in groundwater close to soil surface, inadequate drainage.		
	Lowering of water table	Where extraction of groundwater exceeds natural recharge capacity	Depth to water table	
	Increased stoniness	Associated with extreme levels of soil erosion	Stone and gravel fractions Dry sieving – 2 mm mesh	
Chemical degradation	Salt-affected soils = 950 M ha Chemically degraded= 146 M ha	Salinization Sodication: increase of sodium cations (Na^+) on the soil particles; tends to occur naturally especially in areas where the water table fluctuates.	Salinity, Alkalinity	Electrical Conductivity
			Sodicity	Exchangeable Sodium %), Sodium Adsorption Ratio
			Mineralization	
			Denitrifcation	
	Acidification	Extremely acid soils: usually in high rainfall areas	pH	
Biological degradation	Soil fertility decline	Degradation of soil physical, chemical, and biological properties, leading to reduced soil productivity through: • Reduction in SOM • Decline in soil biol. activity • Loss of soil biodiversity • Degradation of physical prop. • Changes in soil nutrient stock • Nutrient deficiencies/toxicities	Nutrients: N, P, K, others; Soil Respiration (CO_2 Evolution); Soil Organic Carbon (SOC); Microbial Populations; Mycorrhizae	

Source: Adapted from Nair et al. (2011)

Table 18.2 Causes and Extent of Global Land Degradation

Causes of degradation	Description	Estimated Extent of area (Million ha)
Deforestation	Large-scale logging and clearance for farm and urban use, mainly for food production	580
Overgrazing	Affects about 20 % of the world's pasture and rangelands, especially severe in Africa and Asia	680
Fuelwood gathering	About 1730 million m^3 of fuelwood are harvested annually from forests and plantations in the tropics	137
Agricultural mismanagement	Results in water erosion causing severe soil losses, soil salinization and waterlogging	550
Industry and urbanization	Urban growth, road construction, mining and industry cause land degradation in different regions	19.5

Source: UNEP (2004): GEO (Global Environment Outlook) 3: Past, present and future perspectives

in their spatial distribution." Unfortunately, there are no continuously monitored indicators of soil condition that would permit quantitatively based assessments of changes (degradation) over time, comparable to the monitoring of deforestation.

18.7 Agroforestry for the Control of Soil Erosion and Land Degradation: Some Notable Large-Scale Field Projects in the Tropics

As mentioned in Section 18.4.4, soil conservation including control of soil erosion and land degradation was a major activity of several large-scale agricultural development programs in many developing countries of the tropics with the external support of various multinational and bilateral aid agencies during the last three decades of the 1900s. The emphasis of most of these projects was on "doing things on the ground for solving the problems" and they had only a limited – if at all – research component. Although the outcomes of the efforts have not been quantitatively assessed nor resulted in major research publications except in a few cases, the experience has been valuable for designing future development strategies. Being landmark efforts of those times, the experiences from the projects are valuable. Given that these efforts involved a substantial outlay of human and financial resources and their outcomes have probably been not adequately documented, a select few of them are briefly mentioned here.

18.7.1 Country-Specific Projects (Before 2000)

The Majjia Valley Windbreak Project, Niger (http://www.fao.org/3/U7150E/U7150E05.htm): This project undertaken by CARE (Cooperation for Assistance and Relief Everywhere) with the support of USAID (the US Agency for International Development) in the Majjia Valley in Central Niger is perhaps the most widely-mentioned study to date of windbreaks in the Sahel. In the region with favorable soils and 425 mm mean annual precipitation, neem trees (*Azadirachta indica*) spaced 4 * 4 m were planted in double rows starting in 1974 (USAID 1987), establishing over 350 km of windbreaks protecting 3000 hectares of millet and sorghum (*Sorghum bicolor*) fields. An average neem tree yields between 3 and 7 kg of usable fuelwood per year, once the trees attain maturity for wood harvesting in about six years after planting (USAID 1987; Vandenbeldt 1990).

Agroforestry and Sustainable Resource Conservation, Haiti: Haiti is the poorest country in the Western Hemisphere. Repeated natural disasters such as earthquakes and human mismanagement causing severe deforestation (see Chapter 1, Figure 1.7) have caused probably the worst-case scenario of extreme degradation of the once-fertile land leading to the devastation of an entire country in the modern era. Many resource conservation initiatives have promoted agroforestry techniques for reducing soil erosion and improving soil fertility in Haiti. The most extensive has been "*Pwoje Pyebwa*," the Pan American Development Foundation's USAID-supported Agroforestry Outreach Project. Over a 20-year-period from 1981, the project provided over 200,000 smallholder farmers with about 48 million free seedlings of native high-value fruit trees and some exotic species for planting on their sloping, small farm-holdings (Figure 18.18). The project is a frequently quoted example of a large-scale, soil-conservation-oriented agroforestry implementation with the participation of smallholder peasant farmers (Bannister and Nair 1990; Bannister and Josiah 1993; Murray and Bannister 2004; https://projects.Ncsu.edu/project/cnrint/Agro/PDFfiles/HaitiCaseStudy041903.pdf –).

"Grain for Green": China's massive farmland afforestation program: The Grain for Green Project (GGP), also known as the Sloping Land Conversion Program, initiated in 1999, is the biggest ecorestoration program in China. The Program pays farmers to plant trees on their land and provides degraded land to rural families for ecorestoration. The primary objective was to reduce soil erosion and improve the ecological conditions of the Loess Plateau, a severely degraded region located in the upper and middle reaches of the Yellow River. The program subsequently was extended to other provinces. To ensure grain self-sufficiency for the farmers, measures such as building terraces and water-saving irrigation channels have been undertaken. Implementation of the project has induced significant improvement in the vegetation conditions of the area: between 1999 and 2014, 29.8 million ha of steep sloping cropland and barren land was afforested under this program, and another 5.33 million hectares of sloping cropland is targeted for afforestation by 2020. The GGP is also reported to be an example of Payment for Ecosystem Services (PES) to resolve environmental issues in China; the improvement in vegetation conditions has not only benefitted soil erosion prevention but also promoted carbon sequestration in the Loess Plateau (Zhao et al. 2017).

Figure 18.18 Establishment and management of live hedgerows of fast-growing, coppicing, nitrogen-fixing trees such as *Leucaena leucocephala* (as shown in the photo) and *Gliricidia sepium* on farmers' sloping fields was the main technical component of the large USAID-funded agroforestry project in Haiti during the 1980s and the 1990s. (Photo: PKR Nair 1988)

18.7.2 Multi-country Projects (Current: Post 2015)

Regreening Africa (https://Regreeningafrica.org). Regreening Africa is an ambitious five-year project (2018–) that aims at reversing land degradation among 500,000 households and across one million hectares using agroforestry technologies in eight countries in sub-Saharan Africa: Ethiopia, Ghana, Kenya, Mali, Niger, Rwanda, Senegal, and Somalia. Primarily funded by the European Union, with the scientific support of ICRAF, the project is undertaken by a network of international and national non-governmental organizations including World Vision, CARE International, Catholic Relief Services, Oxfam International, and Sahel Eco.

The Great Green Wall of Africa

The Great Green Wall of Africa (GGW) is a pan-African initiative to combat desertification in the Sahara Desert and the Sahel (Figure 18.19). Originally conceived as a massive tree plantation crossing the African continent from west to east, the GGW has evolved into a set of restoration projects aimed at environmental and human well-being. While the GGW is no longer a simple wall of trees as originally envisaged by political actors, plants and re-vegetation remain at the heart of the project because, more than anywhere else, the people of the Sahel depend heavily on plant resources to meet their daily needs. The challenge is to find a balance between the protection and sustainable use of plant resources in the Sahel undergoing a social and ecological transformation (Goffner and Peiry 2020).

18.7.3 "Biodrainage" and Agroforestry for Reclamation of Saline Soils

Soil salinization is a major process of land degradation that is impacting vast areas of farmlands in North America, Central- and South Asia, China, and Australia. In Australia, for example, soil salinization, described as "the silent disaster," is the most severe environmental problem, causing a

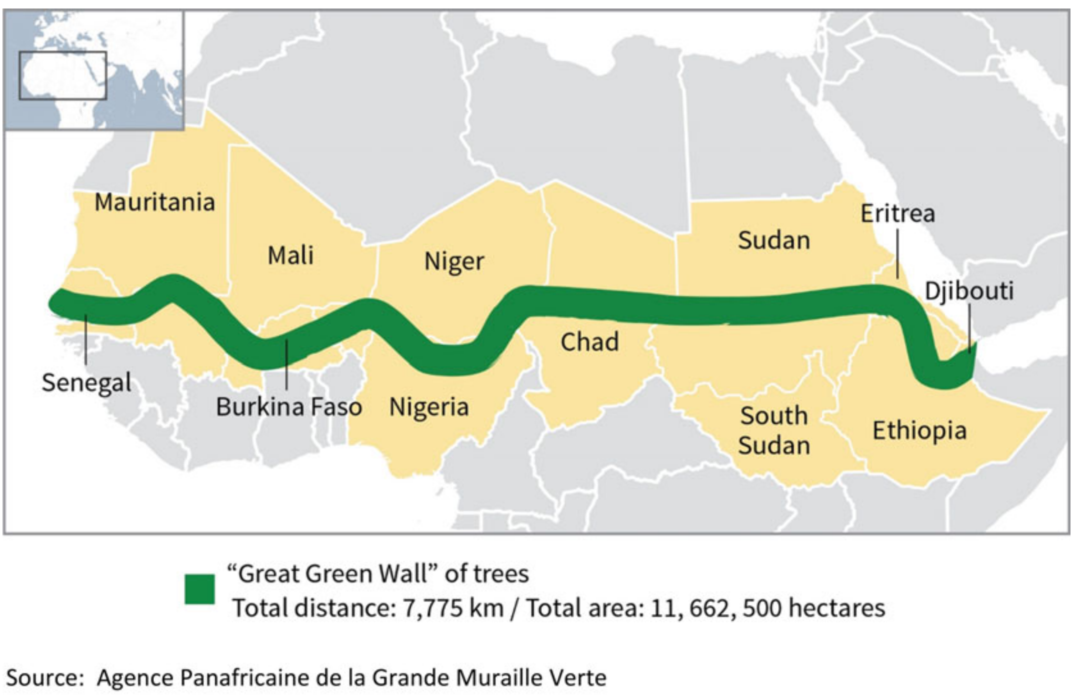

Figure 18.19 The Great Green Wall of Trees across North Africa: A massive project involving seven countries of the region and various multinational development assistance agencies

dramatic change in landscape, industry, and the future of farmland (Clarke et al. 2002). Natural soil salinization, referred to as "primary salinization," occurs by natural causes in arid and semiarid climatic zones; "secondary salinization" refers to that caused as a consequence of direct human activities. The accumulation of soluble salts in soil occurs when evaporation exceeds precipitation and salts are not leached out but remain in the upper soil layers in low-lying areas. The quality of irrigation water is also a major contributor to soil salinity. Irrigation with marginal water (e.g., brackish water and wastewater) with a high content of soluble salts directly affects soil salinity. Nearly one billion hectares of arid and semiarid areas of the world are salt-affected, about 20% of the irrigated area is facing secondary salinization, one-third of which is threatened with waterlogging (FAO 2002). In shallow groundwater conditions, water and dissolved salts move by capillary action to the soil surface. When water evaporates from the surface, the salts are left behind, raising the salt concentration in the soil water above 1.5%, which is the salt concentration inside a normal plant cell. That prevents the osmotic movement of water into the roots, thereby dehydrating the plant.

Biodrainage or biological drainage that refers to the use of vegetation to manage water fluxes in the landscape is a technique that has attracted interest lately in drainage and environmental management circles. It relies on vegetation rather than engineering mechanisms to remove excess soil water through evapotranspiration. The concept is that planting appropriate "biodrainage species," including trees, in proper management systems and harvesting the biomass like wood and/or fodder could achieve gradual soil-improvement while providing economic returns. Dagar et al. (2016) reported that block plantations of *Eucalyptus tereticornis* were effective in increasing water table drawdown in the waterlogged saline soils of northwestern India. Several other species of *Eucalyptus* (e.g., *E. camaldulensis*, *E. tereticornis*, *E. urophylla,* and *E. grandis*) and other trees of the genera *Acacia, Azadirachta, Dalbergia, Casuarina, Hardwickia, Prosopis,* and *Ziziphus* have also been tried successfully (Roy et al. 2016). Dagar and Minhas (2016a, b) have suggested that agroforestry combinations could be developed based on such tree planting efforts. Rigorous scientific results studies in support of these promising claims have, however, still not been reported.

On the other hand, some reports show that changes in vegetation can have opposite effects. Since deep tree roots can efficiently pump underlying shallow groundwater, afforestation of grasslands reverses the vertical flux of groundwater from the soil to the saturated zone. Consequently, plantation could reduce groundwater recharge and cause salinization of the soil and shallow groundwater, as reported based on studies on tree establishment on grasslands in the northern Caspian region (Sapanov 2000), Australia (Heuperman 1992), and the Pampas of Argentina (Jobbágy and Jackson 2004). Nevertheless, the use of biodrainage tree species in agroforestry combinations seems to be an interesting area for research to support salinity mitigation in vast areas of semiarid and arid lands.

18.8 Concluding Remarks

Soil erosion and land degradation have been serious problems in land management throughout the world since the very early times. But the importance of soil conservation was brought to focus in the 1930s following the devastating drought and subsequent wind erosion in the Great Plains of the United States during the era of the Great Depression. The first organized effort to address the problem of soil erosion was to undertake a massive tree-planting program when two hundred million wind-breaking trees were planted across the Great Plains. Subsequently, soil conservation programs spread to other countries, and the effectiveness of tree-based systems in soil conservation became a part of agricultural development policy in the tropics since the 1970s. Thus, right from the early days of agroforestry development, soil conservation and agroforestry became two mutually "dependent" major components of land management. The concept of soil conservation also evolved over the years to encompass both soil-erosion control and maintenance of soil fertility. Land degradation is a broader term than soil conservation. Although defined variously, all its definitions imply the same meaning, i.e., "any change or disturbance to the land perceived to be deleterious or undesirable." Soil erosion is a major form of land degradation, and soil erosion control and soil conservation are important steps in arresting land degradation.

Soil erosion is caused primarily by water (water erosion) and wind. Other causative factors include gravitational force (in steeply sloping bare lands), ice (glaciers), and snow. The process of erosion by both water and wind involves detachment of the soil particles from the soil mass, their transportation, and deposition at varying distances from the original site depending on several site-specific factors and severity and strength of the erosive forces.

The rates and quantities of soil erosion are difficult to be measured precisely. Therefore, they are usually estimated, rather than measured, using some predictive models based on several measurable or otherwise available factors; these equations are then calibrated using measurements from standardized plots. Under practical conditions, however, such field measurements have some difficulties. Thus, the reported values of soil erosion, as well as the statistics on the extent of areas affected by soil erosion and land degradation at regional and national levels, are arbitrary to varying extents.

Various control measures have been proposed and practiced for addressing soil erosion and land degradation. Most of them, however, is based more on experience than on science. It may not be an overstatement to say that the science of this aspect of land management has received relatively less attention compared with other aspects (e.g., soil fertility and plant nutrition). The common agronomic measures include reduced (minimum/conservation) tillage and installation of vegetative barriers and contour hedges, and are designed around the importance of retaining as much plant residues as possible on the land. This has led to the revival and increasing use of some agroforestry practices such as contour planting of multipurpose (fodder and fruit) trees in association with other species – practices that have been used for a long time in sloping lands, especially in the smallholder systems of the tropics.

The establishment of trees as windbreaks and shelterbelts is a practice that is commonly recommended and now getting adopted in many wind-erosion-prone regions of the temperate as well as tropical regions. In addition to the massive and historic Great Plains Shelterbelt project initiated in 1934, several national windbreak/shelterbelt programs backed up by scientific research have been implemented in the vast plains and prairies of Canada and the US. Some large-scale windbreak/soil conservation projects have been implemented in the tropics too with international support since the 1980s, and some new ones have been initiated recently (after 2015). Tree planting either in blocks or in agroforestry configurations has also been being tried for biodrainage and amelioration of soil salinity and waterlogging in vast salt-affected regions in the arid and semiarid lands.

Many, if not most, of all such efforts of soil conservation and land-degradation control, are centered around tree planting. What needs to be emphasized, however, is that trees *per se* do not prevent erosion or land degradation; indeed, a tree in the wrong place can aggravate erosion when surging rainwater finds its way around a standing tree. A fundamental principle to be followed is that keeping an effective land cover as plant canopies or residues is one of the best ways of promoting soil conservation. There are not too many land-use systems that fit that description better than agroforestry systems.

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Section V

Ecosystem Services of Agroforestry

Ecosystem Services of Agroforestry: An Introduction

19

Contents

Abstract

Ecosystem services (ES) are *the benefits that people obtain from ecosystems.* The term became popular in both scientific literature and common parlance around the turn of the century. The concept of ecosystems as *the organisms and the non-living environment with which they interact* has been popular for a long time, but it was not until the latter part of the twentieth century that its relevance started getting recognized and the study of the environment and environmental conservation became prominent. The Millennium Ecosystem Assessment, 2005, carried out by the United Nations with the involvement of all its member states, was a significant landmark in ecosystem research and development. It categorized the ES into four broad groups: Provisioning (products from ecosystems, such as genetic resources, food, fiber, fodder, and freshwater), Regulating (benefits from ecosystem processes, such as the regulation of climate, water, and some human diseases), Cultural (non-material benefits from ecosystems through spiritual enrichment, cognitive development, recreation, etc.), and Supporting (biomass production, soil formation, and nutrient cycling, etc. that are necessary for producing all other ES) services. Over the years, ES as applied to agroforestry has come to embrace a wide variety of such services. Two of the prominent ES of AFS – climate-change mitigation and biodiversity conservation are – discussed in Chapters. 20 and 21, respectively. Other, relatively less-studied ones, are clubbed together in Chapter 23.

19.1 Introduction

Environmentalism – the study of the environment and efforts to protect it from damage by human activities – has been a major scientific and geopolitical activity on the global scene since the latter part of the twentieth century. The activity had a rather slow emergence followed by a rapid rise to

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captivate global attention. Since the late 1990s, *Climate Change* that embodies a large suite of issues has been one of the most prominent items discussed and deliberated at all levels of bureaucratic and administrative systems at national and international levels. As described in Chapter 1, the emergence of agroforestry was also linked to this new wave of enthusiasm in major environmental concerns such as deforestation and soil degradation. Inherent in this approach was the perception of the ecosystem, i.e*., the organisms and the non-living environment with which they interact,* as a whole unit in its entirety rather than in terms of its various components and compartments. Subsequently, the enormous importance of the benefits derived from the ecosystems was recognized and the term *Ecosystem Services* (ES) became popular in both scientific literature and common parlance. In simple terms, ecosystem services are *the benefits that people obtain from ecosystems.* As is common with all such terms that attain sudden prominence, this term is also used out of context. Ecosystem mismanagement may also cause "disservices" (i.e., unintended consequences that could be harmful to humans).

Right from the beginning of efforts in modern agroforestry, the production of goods (productive role) and provision of services (protective role) have been treated as its two fundamental and equally important attributes (see Chapter 2, Section 2.4). Over the years, the reference to *ecosystem services as applied to agroforestry* has come to embrace a wide variety of services that contribute to an environment that enables and supports the sustainable production of goods and materials of economic, social, and ecological importance and significance to humans. Numerous such services have been recognized, including but not limited to, soil productivity and protection, climate change mitigation, biodiversity conservation, hydrological balance, and ecosystem integrity. Of these, soil productivity and protection (conservation) aspects have been discussed in the previous section (Section IV) of this book. The current section will consider the role of agroforestry in the other major aspects of ecosystem services such as climate-change mitigation and biodiversity (BD) conservation. There may be disagreements among experts as to whether any of these services should be considered as specific services of their own or as subsets of the broad concept of ecosystem services; for example, some may argue that BD conservation by and of itself the issue of paramount importance to the extent that when BD is conserved, other benefits such as climate-change mitigation will be natural consequences. Although such discussions are of academic merit, in most discussions and action plans, BD conservation is considered as one of the major and highly valued benefits of the overall ES. Detailed treatment and discussions on such "mega issues," for which enormously voluminous literature is available and new ones are coming out incessantly, are not within the scope of this book. Here, the treatment of the issues will be oriented to the role of agroforestry in attaining the desirable ecosystem services, i.e., how AFS can contribute to BD conservation, climate change mitigation, and so on.

19.2 Global Assessments of Ecosystem Services

The modern notion of "environmental services" arose in the 1970s (Wilson and Matthews 1970), although the idea itself is probably much older. Re-named as "ecosystem services" (ES) in the mid-1980s (Ehrlich and Mooney 1983), it started gaining popularity in the late 1990s. A significant landmark in ES research and development was a major global initiative, the Millennium Ecosystem Assessment undertaken by the UN (United Nations) (MA 2005). The Assessment, carried out with the involvement of all member states of the United Nations, underscored the idea that human well-being depends on ecosystems, and that the interrelationships among the components of the ecosystem and their combined effects on humans could be monitored through the framework of ES. The MA defined ecosystem services as "the functions and products of ecosystems that benefit humans, or yield welfare to the society." The Assessment provided a state-of-the-art synthesis of the condition and trends in the world's ecosystems and the benefits they provide, as well as the scientific foundation for their conservation and sustainable use. While the MA treated the concept of "ecosystem goods and services" synonymous with ES, it also highlighted that more than 60% of ES are being degraded or transformed by anthropogenic factors, jeopardizing future human well-being.

The Millennium Ecosystems Assessment categorized the ecosystem services into four broad categories (Table 19.1):

- **Provisioning services**: The products obtained from ecosystems, including, for example, genetic resources, food and fiber, and freshwater.
- **Regulating services**: The benefits obtained from the regulation of ecosystem processes, including, for example, the regulation of climate, water, and some human diseases.
- **Cultural services**: The non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience, including, e.g., knowledge systems, social relations, and aesthetic values.
- **Supporting services**: Services that are necessary for producing all other ecosystem services. Some examples include biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

The MA classification provided a comprehensive basis to initiate ES research and applications. Subsequently, however, some concerns have been expressed that it does not symbolize a sound taxonomy, and there is ambiguity across typologies (Notte et al. 2017). For instance, food is both a provisioning service and a cultural service in many cultures (https://www.ipbes.net/glossary/ecosystem-services). Likewise, certain supporting services such as nutrient cycling and production of atmospheric oxygen are now widely considered as an ecosystem property rather than a service *per se* (https://www.ipbes.net/event/ipbes-5-plenary).

The MA classification was subsequently modified (replaced) in the assessments by IPBES (Intergovernmental Science-Policy Platform on

Table 19.1 Categories of ecosystem services with examples

Type of service	Service
Provisioning services	Food
	Fiber
	Genetic resource
	Biochemicals, natural medicines, etc.
	Ornamental resources
	Fresh water
Regulating services	Air quality regulation
	Climate regulation
	Water regulation
	Erosion regulation
	Disease regulation
	Pest regulation
	Pollination
Cultural services	Cultural diversity
	Spiritual and religious values
	Recreation and ecotourism
	Aesthetic values
	Knowledge systems
	Educational values
Supporting services	Soil formation
	Photosynthesis
	Primary production
	Nutrient cycling
	Water cycling

Source: Adapted from MA (2005)

Biodiversity and Ecosystem Services), an "intergovernmental body which assesses the state of biodiversity and of the ecosystem services it provides to society, in response to requests from decision-makers" (https://www.ipbes.net/). The primary argument in support of this change was "category overlap," which implies that many services fit into more than one of the four categories of the MA framework (Notte et al. 2017). The IPBES, therefore, introduced the notion of *nature's contributions to people* (NCP: initially termed *Nature's Benefits to People*), considering "all contributions of nature to the quality of life of humans (both positive and negative) as NCP" (IPBES 2017, Diaz et al. 2018, Torralba et al. 2016). Another important frame of reference for ES research is the Common International Classification for Ecosystem Services (CICES), proposed by the European Environment Agency (Maes et al. 2016). The CICES categorizes ecosystem outputs into three categories: *provisioning, regulating, and cultural services* (https://cices.eu/cices-structure/). Despite all these developments, ES and NCP are widely used synonymously, and the MA framework (Table 19.1) continues to be the most recognized classification of ecosystem services, and that will be used in this book.

19.3 Ecosystem Services of Agroforestry

Agroforestry systems provide an array of ecosystem services, as summarized in Table 19.1 and Figure 19.1. What contributes to the ability of agroforestry systems to deliver a variety of ecosystem services is the relatively high species diversity as illustrated in the earlier sections of this book, especially Chapters 7, 8, and 11, compared to silvicultural and agricultural monocultures. The exceptionally high species richness of the "biodiverse" agroforestry systems composed of multiple components of various forms of plants leads to high levels of structural

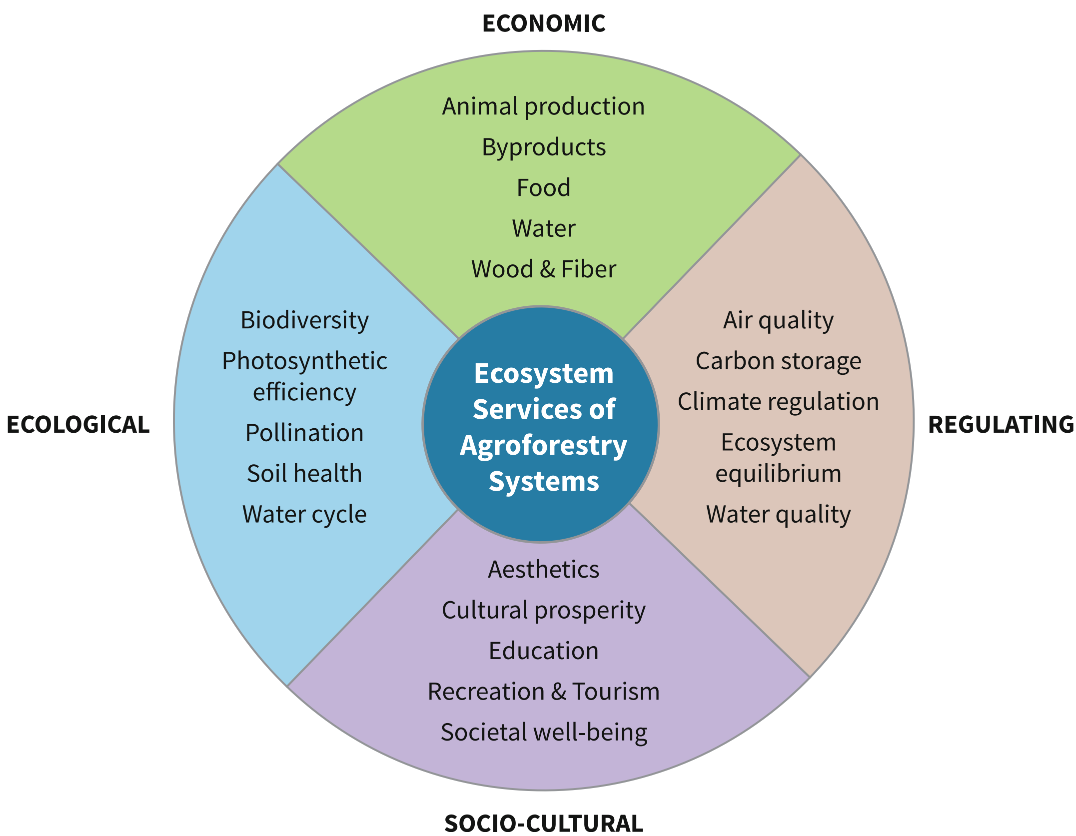

Figure 19.1 Ecosystem services. Adapted from https://winnebagroforest.org/homepage-articles-archive/ecosystem-services/

and functional complexity and multifunctionality, which is the cornerstone of various ecological processes underlying the ecosystems services.

Several studies have quantitatively assessed the potential of agroforestry systems to conserve biodiversity and to provide ES (Table 19.2). Torralba et al. (2016) found that European agroforestry systems exert a significant positive effect on biodiversity conservation and ES provision compared to conventional systems, specifically concerning nutrient cycling, biodiversity conservation, and erosion control. In a recent meta-analysis on the effects of agroforestry systems on biodiversity and ES in the Brazilian Atlantic Forest, Santos et al. (2019) highlighted that a biodiverse agroforestry system is the best option to

Table 19.2 Examples of systematic reviews and meta-analyses describing the interdependence of biodiversity and ecosystem services in agroforestry systems (since 2010)[a]

Reference	Description of the study	Major findings
Barrios et al. (2018)	Information from six agroforestry and tree cover transition studies, spanning tropical/subtropical forest zones in three continents (Asia, Africa and North America), at locations described as biodiversity 'hotspots' were synthesized to assess the contribution of tree cover to the conservation of biodiversity and ecosystem services.	Reduction in native earthworm populations caused 76% lower soil macroporosity, when shade trees were absent in coffee agriculture. But increased tree cover contributed to 53% increase in tea crop yield, maintained 93% of crop pollinators found in the natural forest and, in combination with nearby forest fragments, contributed to as much as 86% lower incidence for coffee berry borer.
Beenhouwer et al. (2013)	A global quantitative synthesis employing meta-analytical approaches and mixed models on data from 74 studies across Africa, Latin America and Asia, to assess the impact on biodiversity and on ecosystem services of (i) the conversion of natural forest into cacao and coffee agroforestry and (ii) the further intensification of agroforest into cacao and coffee plantation.	More intensively managed systems had significantly lower forest species richness and total species richness than that of the more natural land use categories. Response ratios showed that the decline in total species richness was higher when comparing agroforest with plantation (−46%), than when comparing forest with agroforest (−11%). Biodiversity responses to intensification differed between Asia and Latin America, and between different species groups.
Dawson et al. (2014)	Analysis based on the FAO Report 'State of the World's Forest Genetic Resources' (FAO 2014a).	Tree-based production systems are promoted because of their perceived biological, economic and social resilience in the context of anthropogenic climate change and other production challenges. Smallholders use a wide range of trees. The study also provides information on the value of trees to rural communities in the context of both the level of tree domestication that has taken place and the management setting.
George et al. (2012)	Literature review aimed to assess the potential of Australian land use systems that mimic natural systems and explore how markets for carbon, biodiversity and salinity improvement can be used to fund transformational, landscape-scale changes.	Aboveground ecosystem productivity and biodiversity were intimately linked but only a few observational studies illustrate this trend.
Kremen and Miles (2012)	Reviewed the literature that compares biologically diversified farming systems (DFS) with conventional farming systems (CFS) and examined ecosystem services.	DFS supported substantially greater biodiversity, soil quality, carbon sequestration, and water-holding capacity in surface soils, energy-use efficiency, and resistance and resilience to climate change compared to CFS. DFS also showed enhanced control of weeds, diseases, and arthropod pests and exhibited increase pollination services.

(continued)

Table 19.2 (continued)

Reference	Description of the study	Major findings
Letourneau et al. (2011)	Meta-analysis on 552 experiments in 45 articles to test if plant diversification reduce herbivores and/or increase the natural enemies of herbivores as predicted by associational resistance hypotheses, the enemies hypothesis, and attraction and repellency model applications in agriculture.	Herbivore suppression, enemy enhancement, and crop damage reduction effects were substantially stronger on diversified crops than on crops with none or fewer associated plant species. Pest-suppressive diversification schemes, however, interfered with production, in part because of reducing densities of the main crop by replacing it with intercrops or non-crop plants.
Nicholls and Altieri (2013)	Reviewed the literature providing evidence that the restoration of plant biodiversity within and around crop fields can improve habitat for domestic and wild bees as well as other insects and thus enhance pollination services in agroecosystems.	Certain weed species within crop fields that provide food resources and refuge within crop fields aid in the survival of viable populations of pollinators. But careful manipulation strategies are needed to avoid weed competition with crops and interference with cultural practices.
Pumarino et al. (2015)	Meta-analysis on 42 studies on the effects of agroforestry on the abundance of invertebrate pests, weeds, natural enemies and plant damage due to pests and diseases and whether the effects of agroforestry were dependent on crop type (annual or perennial), type of pest association (above or belowground) and weed type (parasitic *Striga* weeds or non-parasitic weeds).	Agroforestry practices resulted in lower abundances of both parasitic and non-parasitic weeds, and in higher abundances of natural enemies. Perennial crops (e.g. coffee, cocoa and plantain) and agroforestry were associated with lower pest abundances and less plant damage.
Santos et al. (2019)	A meta-analysis of 72 studies encompassing 143 study sites and 1700 comparisons to quantify the effects of different types of agroforestry systems on biodiversity and ES in the Brazilian Atlantic Forest.	Biodiverse agroforestry systems reduced biodiversity loss and the negative impact on ES. Agroforestry systems provide up to 45% and 65% more benefits for biodiversity and ES levels, respectively, than conventional production systems; however, these benefits differ according to the type of agroforestry system.
Torralba et al. (2016)	A meta-analysis of European agroforestry systems on providing ecosystem services and biodiversity; 53 publications and a total of 365 comparisons.	Agroforestry can enhance biodiversity and ecosystem service provision relative to conventional agriculture and forestry in Europe and could be a strategically beneficial land use in rural planning if its inherent complexity is considered in policy measures.
Tscharntke et al. (2011)	A review of the short-term and long-term ecological benefits of shade trees in coffee (*Coffea arabica*, *C. canephora*) and cacao (*Theobroma cacao*) agroforestry to highlight the multifunctional role of shade trees for farmers and conservation.	Shade trees in agroforestry enhance functional biodiversity, carbon sequestration, soil fertility, drought resistance as well as weed and biological pest control. Short-term yield gains through shade removal may reduce the long-term resistance and resilience of the system, due to pest pressure, vulnerability to changing climate and difficulties to rejuvenate cacao. Reducing canopy cover from 80% to 40%, however, can double the income of local farmers with only minor changes in biodiversity and associated ecosystem services.
Tsonkova et al. (2012)	Literature review of selected ecosystem services from temperate European alley cropping systems (ACS).	ACS increases carbon sequestration, improves soil fertility and generally optimize the utilization of resources. Owing to their structural flexibility, ACS may also help to regulate water quality, enhance biodiversity, and increase the overall productivity.

(continued)

Table 19.2 (continued)

Reference	Description of the study	Major findings
Wratten et al. (2012)	Literature review to identify the secondary benefits of pollinator habitat enhancement, including the protection of general wildlife biodiversity, the enhancement populations of other beneficial insects (those that prey upon or parasitize crop pests), the protection of soil and water quality, and the enhancement of rural aesthetics.	Agri-Environmental Schemes for promoting pollinator habitat not only improved forage and nesting resources for bees but also contributed to the general protection of biodiversity, greater natural pest control, improved soil and water quality, and enhanced rural aesthetics.

[a]IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) assessments are a major effort in this direction. As on this date, eight voluminous reports have been produced. These are on Pollination, pollinators and food production; Land Degradation and Restoration; Biodiversity and Ecosystem Services for Europe and Central Asia; Biodiversity and Ecosystem Services for Asia and the Pacific; Biodiversity and Ecosystem Services for Africa; Biodiversity and Ecosystem Services for the Americas; Scenarios and Models of Biodiversity and Ecosystem Services; and Global Assessment Report on Biodiversity and Ecosystem Services. It is, however, impossible to summarize those reports here. Interested readers may download the reports in full from the IPBES website (https://www.ipbes.net/)

enhance biodiversity and ES in degraded areas. Thus, scientific evidence on the role of agroforestry systems as an alternative method to recover degraded lands in human-dominated landscapes is increasing.

It may, however, be noted, natural ecosystems have a greater potential to provide ES than agroforests and plantations. Based on a meta-analysis on 74 studies across Africa, Latin America, and Asia, Beenhouwer et al. (2013) reported that coffee and cacao agroforests provided only 63% of the ES of forests, while forest plantations provided 73% of that of agroforests. They also found that response ratios declined by a significant 11% in total species richness with management intensification from forest to agroforest and 46% once agroforest was converted to plantation (Figure 19.2).

A group of ICRAF scientists identified and articulated (Rosenstock et al. 2019) the various facets of the effects of agroforestry on land management and human life (i.e., the ecosystem services) across sub-Saharan Africa based on a comprehensive review of literature, supplemented by the researchers' extant personal experiences across the continent. The studies, mostly on field-scale effects, concluded that the major effects of agroforestry on the environment include interception of sunlight, lowering of ambient temperatures, reduction in evapotranspiration, increase in water use in some cases, improvement of soil water-holding capacity and water infiltration, and enhancement of carbon storage and biodiversity. Earlier, Kuyah et al. (2016) had reported a somewhat similar but less extensive study from sub-Saharan Africa (Figure 19.3). Integrating both these studies, Rosenstock et al. (2019) concluded that in about 60% of cases where the agroforestry-environment relationship was investigated, trees improved the delivery of ecosystem services as summarized in Table 19.3. Although most of the studies showed largely positive impacts, several (number not specified) studies showed negative or non-significant effects of agroforestry, which the authors considered as indicative of the possibility of diverse, often site-specific, and unintended outcomes when managing land with trees.

As mentioned in Section 19.2, the four categories of ecosystem services proposed by the Millennium Ecosystem Assessment (provisioning, regulating, supporting, and cultural) are widely accepted (Table 19.1). The boundaries of the different categories, however, are often faint, such that considerable overlaps exist among the different categories, as indicated in Section 19.2. Each major ES such as climate change mitigation or biodiversity conservation will entail elements of more than one category of services; what may be listed as provisioning services may sometimes be considered as regulating or supporting services, and cultural services may have elements of all other categories of service, and so on. Therefore, while discussing the various ES

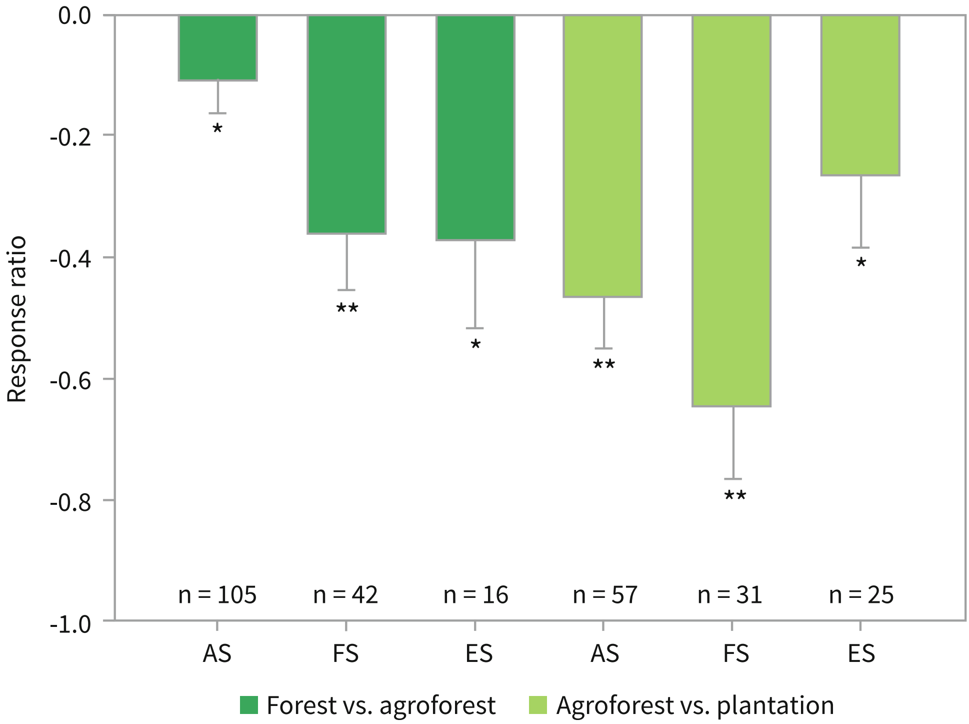

Figure 19.2 Response ratios for species richness and ecosystem services in forest vs. agroforest; and agroforest vs. plantation. Response ratios, significantly different from zero are indicated (*$p < 0.05$ and **$p < 0.01$). Flags are standard errors. AS = all species, FS = forest species, and ES = ecosystem services. Adapted, with permission, from Beenhouwer et al. (2013)

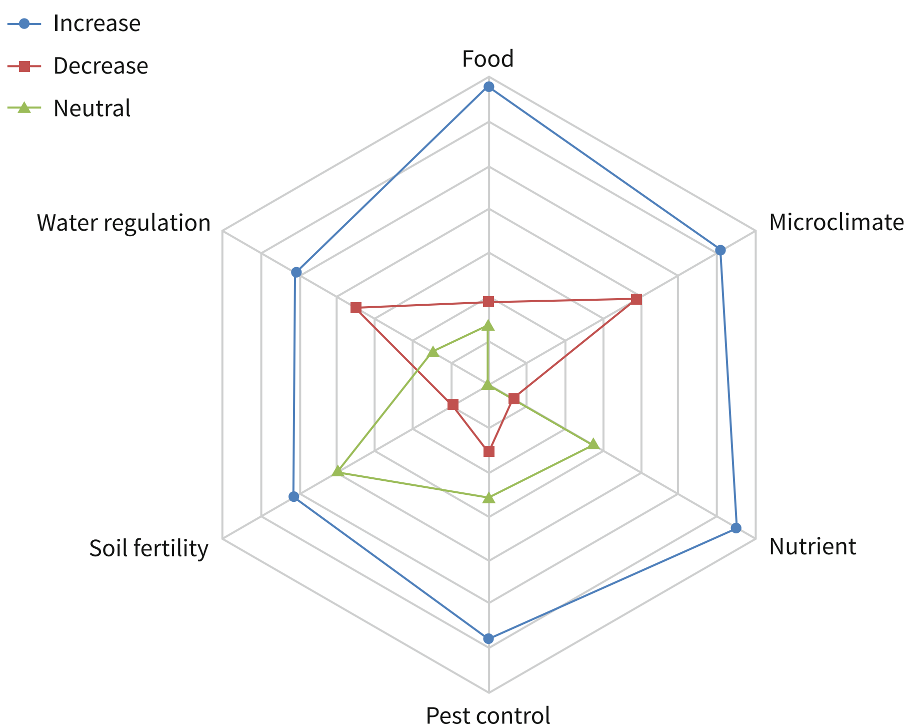

Figure 19.3 Proportions of ecosystem services that increase and decrease by the presence of trees on landscapes in sub-Saharan Africa. Source: Kuyah et al. (2016)

Table 19.3 Impact of agroforestry on ecosystem services in Africa

Ecosystem services	No. of studies[a]	Significant Effect (%)		
		Positive (+)	Negative (−)	Non-significant
Microclimate	18	61	39	n.a.
Nutrient cycling	128	59	8	33
Water dynamics	69	51	35	14
Soil fertility	156	59	3	38
Biodiversity	25	56	16	28

[a]Total n = 207 studies; column total is not the sum of numbers in the cells because some studies included multiple ecosystem services
n.a. = not available
Source: Rosenstock et al. (2019)'s adaptations from Kuyah et al. (2016)

of agroforestry systems, it is realistic and pragmatic to consider the major recognized services *per se* rather than the various MA-categories of services. For that reason, the prominent (studied) ES of AFS are discussed in separate chapters: 20 (Climate Change and Carbon Sequestration) and 21 (Biodiversity Conservation). Other, relatively less-studied ones are clubbed together in a separate chapter: 23 (Other Ecosystem Services).

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Carbon Sequestration and Climate Change Mitigation

20

Contents

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_20

Abstract

This chapter examines the role of agroforestry in carbon sequestration (CS) and climate-change mitigation (CCM) based on the scientific hypotheses, research results, and observations accumulated so far. Since the emergence of climate change (CC) as a prominent global issue in the late twentieth century, agroforestry has received immense attention as a land-management strategy with considerable potential for addressing it. The underlying premise is that photosynthetic carbon capture by trees is an effective strategy for limiting the rise of CO_2 concentrations across the globe, and agroforestry systems (AFS), compared with treeless agricultural systems, would lead to higher rates of CS. Following an overview of the commonly used technical terms, the chapter describes the extent, causes, and consequences of climate change; a summary of the global developments in the subject; the mechanisms of soil CS (SCS); and the importance of soil aggregates in SCS. Field research data on SCS reported from multilocational investigations in AFS in different ecological regions of the world as well as meta-analyses of reported results corroborate the higher C storage in AFS compared to single species cropping and grazing systems in both aboveground biomass and soils, especially at lower soil depths. Thus, the adoption of agroforestry practices can be a safe bet for CS and CCM. Brief accounts of some research initiatives and development paradigms related to soil carbon management for CCM are also included in the chapter. These include the potential use of biochar in AFS, and global activities such as *Carbon Farming, One Trillion Trees Around the Globe, Regenerative Agriculture, and Soil Carbon Four per Mille (4p 1000).*

20.1 Introduction

Climate-related issues have always been a significant factor in land management for agriculture and other forms of land use. Since the late 20th century, however, "Climate Change" has captivated global attention at an unprecedented level and magnitude. The United Nations describes it as "the defining issue of our time" and emphasizes that "from shifting weather patterns that threaten food production to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. Without drastic action today, adapting to these impacts in the future will be more difficult and costly" (https://www.un.org/en/sections/issues-depth/climate-change/). The devastating forest fires of Australia during 2019–2020, and California, USA, during 2020 believed to have been fuelled by climate change, have added substantially to the strength of the message: "the impact of climate change that was feared and warned about is no longer in our future – it is here."

Ever since climate change and the related term "global warming" became prominent global issues, agroforestry has received immense attention as a land-management strategy with considerable scope and potential for addressing those issues. This chapter will examine the role of agroforestry in carbon sequestration and climate-change mitigation based on the scientific hypotheses and evidence as well as field results and observations accumulated so far. It will start with a general overview of the "language" (commonly used technical terms), extent, causes, and consequences of climate change, and a summary of the global developments in the subject.

20.2 Climate Change: The Language, Extent, Causes, and Consequences

Following the emergence of climate change as a "hot topic," there has been a veritable explosion of the literature on different aspects of the topic. Voluminous materials of all types and modes – scientific journal articles, popular publications, books, reports, etc. – are available online, in print, and other forms and formats, and new ones are coming out almost every day. To begin with, let us explain a few of the major technical terms in climate-change discussions.

20.2.1 Definition

According to NASA (the National Aeronautical and Space Administration, USA: https://www.nasa.gov/), **climate change refers to "any long-term change in Earth's climate, or in the climate of a region or city."** The related term **global warming** refers to the increasing average global temperature since the Industrial Revolution: the average global temperature has increased by about 0.8 degrees Celsius (1.4 degrees Fahrenheit) since 1880 (Figure 20.1), and this change is believed to be permanently changing the Earth's climate.

20.2.2 Causes of Climate Change: The Greenhouse Gases

It is almost unanimously agreed that climate change – and global warming – are caused by the rise in the atmospheric concentration of the so-called **greenhouse gases** (GHGs). The key GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Among these, CO_2 is the major and most common one, but other gases are relatively more powerful: methane is 25 times and N_2O nearly 298 times more potent than CO_2 (IPCC 2014) in terms of their global warming potential. These are called GHGs because their effect in the atmosphere causes a situation comparable to that in a greenhouse. Solar energy (short-wave radiation) is absorbed by earth's objects and radiated back as long-wave radiation (heat). But the trapping of GHGs in the atmosphere prevents the long-wave radiation from escaping the earth's atmosphere back into space, in a manner analogous to the glass ceiling of a greenhouse permitting sunlight to pass in but trapping the sun's heat within.

The atmospheric concentration of CO_2 that had increased from about 280 ppm in the pre-industrial period to more than 400 ppm in the early 2000s at an average of 2 ppm per year surged to an average decadal rate of 2.4 ppm per year during 2010 – 2019 (Figure 20.1). This

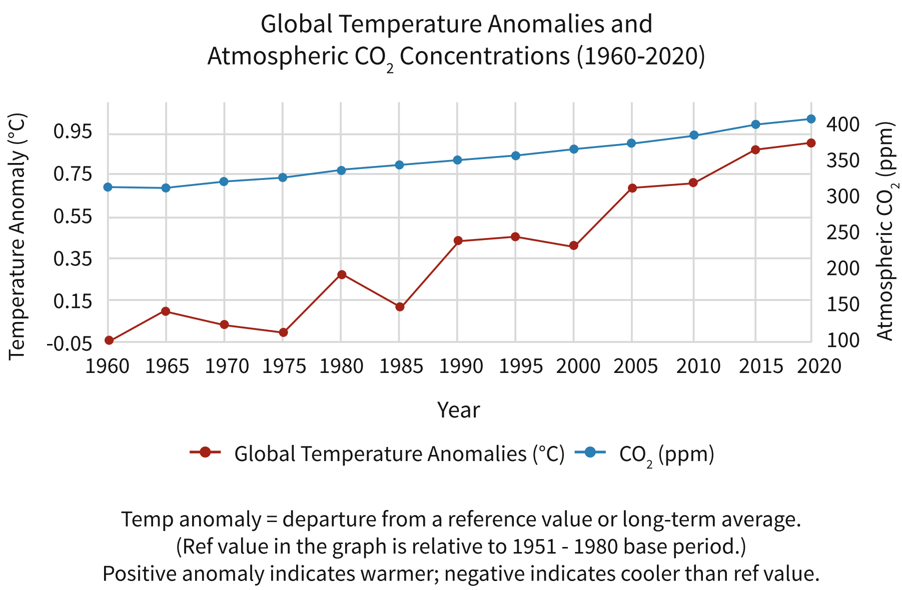


Figure 20.1 Atmospheric carbon dioxide concentrations and increases in temperature from 1960 to 2020

increase is caused by natural and anthropogenic (human-induced) factors. The main anthropogenic factors include the burning of fossil fuels such as coal, gas, and oil for industrial and other purposes; **agriculture, forestry, and other land-use** (AFOLU) including deforestation (see Chapter 1, Figure 1.8); and transportation. These three major groups of factors are estimated to cause 60%, 24%, and 14%, respectively, of global warming. The full effect of warming is likely to continue into the foreseeable future so long as the emission of GHGs continues unabated.

A relatively small but influential group of people commonly referred to as climate-change "deniers" argue that the Earth's climate has always been changing, that no direct cause-effect relationship has been established between GHGs and global temperature, and the temperature has increased only by a mean of less than 1 °C in the past 130 years despite its variability between years. It is common knowledge that political and executive pressures and coercion are involved in a big way in these discussions. The powerful voices of 97% of scientists, the public at large, and numerous celebrities – including the young and famous Swedish activist Greta Thunberg (born in January 2003) – have lent strong support to the call for action to address this global issue very seriously.

20.2.3 The Extent and Impact of Climate Change

The Earth continues to be warmer than it was several decades ago (Figure 20.1). All ten warmest years (except for 1998) in the 134-year documentation have happened since 2000. As per the assessment of NASA's Goddard Institute for Space Studies (GISS), the average global temperature has increased by about 0.8 °C (1.4 °F) since 1880, and 0.6 °C (1.0 °F) since 1970. The Intergovernmental Panel on Climate Change (IPCC) has projected that, by the year 2100, the mean global temperatures could escalate between 1.4 and 5.8 °C (IPCC 2000).

Some of the significant likely consequences of global temperature increase (climate change) include:

1. **Rainfall Patterns**: An increase in air-temperature leads to increased evaporation from soil and water bodies such as rivers, lakes, and oceans, leading to the movement of more water through the global climate system and consequently extra rainfall. The surge in rainfall will, however, be distributed unevenly, with less in the drier areas and more in the wetter, and the rainfall pattern (onset of wet and dry seasons), quantity, and distribution will be unpredictable. All these effects already occur now frequently throughout the world.
2. **Sea-level Rise**: Since warmer air holds more moisture, the increase in temperature leads to an expansion in the volume of water and a rise in sea level. During the past century, ocean levels have levitated 20 cm, and higher levels of sea level rises in the future are predicted. This is critically important since about a seventh of the world's human population lives within about 10 meters of sea level.
3. **Melting of Glaciers and Permafrost**: With increases in the air- and ocean temperatures, the glaciers and ice caps will melt, leading to further sea level rises. The increase in temperature leads to melting of permafrost; the corresponding increase in bacterial activity will lead to faster decomposition of organic matter and release of CO_2 and methane caught in a frozen condition in the Arctic Ocean floor.
4. **Inundation of Low-lying Islands**: The addition of large volumes of water to the world's oceans will lead to the inundation of low-lying islands (as has happened, for example, in the Solomon Islands in the Pacific Ocean in May

2016: http://www.scientificamerican.com/article/sea-level-rise-swallows-5-whole-pacific-islands/).

5. **Ocean Currents, *El Niño/La Niña***: When the ocean surface becomes much warmer than usual, an El Niño is said to occur; a La Niña happens when the reverse situation occurs resulting in a lowering of sea surface temperatures. During an El Niño episode, torrential rains and intense tropical storms may occur in some far-away areas and drought in others.
6. **Indirect Effects:** These include effects on pollinators, pests and diseases, weeds and invasive species, and other ecosystem and environmental services.

20.2.4 Global Initiatives for Combating Climate Change

The publication of the World Commission on Environment and Development (WCED) Report, *Our Common Future*, commonly called the Brundtland Commission Report on Sustainability (WCED 1987), helped to draw global attention to the importance of environmental protection and sustainable use of global resources for the benefit of the planet and future generations. Following various deliberations, the IPCC was established in 1988 under the auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) for assessing "the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change." The IPCC (www.ipcc.ch) does not conduct any research, nor does it monitor climate-related data or parameters. Thousands of scientists from around the world contribute to the work of the IPCC voluntarily. The IPCC bases its assessment mainly on published and peer-reviewed scientific and technical literature. The First Assessment Report of the IPCC, published in 1990, and a supplemental report prepared in 1992 supported the establishment of the **United Nations Framework Convention on Climate Change (UNFCCC). The** UNFCCC treaty was adopted at United Nations Conference on Environment and Development (commonly known as "The Earth Summit") held in Rio de Janeiro, Brazil, in 1992. The treaty is the first major international agreement to combat global warming, and it forms the foundation of international political efforts in this direction. Since then, the so-called UNFCCC **Conference of Parties (COP)** has been held at various places around the world, each involving massive volumes of work leading to the preparation of various IPCC reports. The IPCC Assessment Reports represent thorough, massive, and carefully explained views on the state of climate change science.

After years of gridlock, a new international agreement on Sustainable Development, called the Paris Agreement on Climate Change, was adopted in the December 2015 Summit and ratified by nearly 200 countries. The Agreement aims to keep the increase in global average temperature in the long term to well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C, recognizing that it would substantially reduce the risks and impacts of climate change. Under the Agreement – hailed as historical in the fight against environmental degradation – each country must determine, plan, and regularly report on the contribution that it undertakes to mitigate global warming (the so-called nationally determined contributions or NDCs), but does not force any country to set a specific emissions target by a specific date. The commitment of the United States to honor the Agreement, however, is a major political issue, and the effectiveness of the Agreement will be diminished seriously without the full involvement of the United States. Since the two major political parties in the country are adhering strictly to opposing views on accepting or rejecting the

Agreement, the position, unfortunately, is not clear as of this writing in late November 2020. In summary, discussions surrounding climate change have been happening in a big way, but the world has not yet come together to address the problem effectively.

20.2.5 Climate Change Mitigation and Adaptation

Mitigation and adaptation are two terms that have become widely popular in climate-change literature and discussions.

Mitigation signifies the technological change and substitution that decrease GHG emissions by avoiding emissions and sequestering GHGs. The common strategies for mitigation are (1) avoiding or reducing the emissions through increasing input-use efficiency and (2) sequestering CO_2 in terrestrial biosphere such as in biomass and soil C pools. Adoption of sound management of nutrients and water and appropriate soil and water conservation measures are among the accepted methods for climate-change mitigation.

Adaptation refers to the initiatives and actions that are designed to decrease the susceptibility of natural systems to climate change. These include strategies such as enhancement of soil resilience (augmenting SOC pool, restoring degraded lands) and adoption of efficient land-use practices to reduce the adverse consequences.

Efficient mitigation and adaptation strategies are discussed in more detail later (Section 20.6.2), and the adoption of agroforestry is recognized as one of those effective strategies for both climate-change mitigation and adaptation.

20.3 Carbon Sequestration

Carbon sequestration is an important strategy for reducing atmospheric concentrations of GHGs, especially CO_2, and thereby global warming. The UNFCCC describes it as "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 long-lived pools" (UNFCCC 2007). Plants of all types – especially trees – and the soil are important in C sequestration. Plants absorb atmospheric C for photosynthesis and store the product of photosynthesis in their parts. The soil is a significant C sink. Globally, soil to one-meter depth is estimated to contain 2,300 Pg (1 petagram = 10^{15} g = 1 billion ton) consisting of 1550 Pg as soil organic C (SOC) and 750 Pg as inorganic C. This total soil C pool is three-fold higher than the atmospheric pool (770 Pg) and 3.8-fold higher than the vegetation pool of 610 Pg.

The concept of carbon sequestration is the same across different land-use systems. Although the underlying mechanisms also are similar, they may manifest themselves differently in different systems depending on system-specific characteristics. In this section, we will further elaborate on the earlier-presented general definition and concepts of C sequestration and then discuss the C-sequestration mechanisms under agroforestry systems (AFS).

20.3.1 Definition and Concepts

As mentioned above, carbon sequestration, i.e., the process of removing C from the atmosphere and depositing it in a reservoir, entails the transfer of atmospheric C, especially CO_2, and its secure storage in long-lived pools. The long-term global C cycle that describes the biogeochemical cycling of C among surface systems consisting of the oceans, atmosphere, biosphere, and soil controls the atmospheric CO_2 concentration over geological time scales of more than 100,000 years (Berner 2003). The short-term C cycle over decades and centuries is of greater significance than the long-term cycle in the forest, AFS, and agricultural ecosystems. The important processes of this cycle are the fixation of atmospheric CO_2 in plants through photosynthesis and return of part of that C to the atmosphere through the plant-, animal-, and microbial respiration as CO_2

under aerobic conditions and CH_4 under anaerobic conditions. Vegetation fires, and burning and land clearing for cultivation for agricultural and forestry purposes, can also release significant quantities of CO_2 to the atmosphere; but much of this C is recaptured in subsequent re-growth of vegetation (Lorenz and Lal 2010; Nair et al. 2010). Carbon pools in such terrestrial systems include the aboveground plant biomass, durable products derived from biomass such as timber, and belowground biomass such as roots, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments. Thus, from the agroforestry point of view, C sequestration involves primarily the uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation, detritus, and soil pools for "secure" storage.

The Soil Science Society of America (SSSA) recognizes that C is sequestered in soils in two ways: direct and indirect (SSSA 2001). "Direct soil C sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates." Indirect plant C sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass. Some of this plant biomass is then sequestered as soil organic carbon (SOC) during/following the decomposition processes. The amount of soil C sequestered at a site reflects the long-term balance between C uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land cover and/or land-use practices that affect pools and fluxes of SOC have significant implications for the C cycle and the earth's climate system. Thus, carbon sequestration occurs in two major segments of AFS: aboveground and belowground. Each can be partitioned into sub-segments: the former into specific plant parts (stem, leaves, etc. of trees and herbaceous components), and the latter into living biomass such as roots and other belowground plant parts and soil organisms, as well as C stored in various soil horizons. The total amount sequestered in each part differs greatly depending on several factors, including the region, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use. On average, the soil and aboveground parts hold major portions, roughly 60 and 30 percent, respectively, of the total C stored in tree-based land-use systems (Lal 2005, 2008). Based on the notion that tree incorporation in croplands and pastures would result in greater net C storage above- and belowground, agroforestry systems are believed to have a higher potential to sequester C than pastures or field crops (Kirby and Potvin 2007; Roshetko et al., 2002; Montagnini and Nair 2004; Nair et al. 2009a, 2010; Nair and Nair 2014).

20.3.2 Aboveground (Vegetation) Carbon Sequestration

Aboveground C storage is the incorporation of C into plant matter either in the harvested products or in the parts remaining on-site in a living form. The aboveground biomass (AGB) that is not removed from the site is eventually reincorporated into the soil as plant residues and organic matter. Estimates of aboveground C sequestration potential (CSP) are based on the assumption that the dry weights of 45–50% of branches and 30% of foliage constitute C (Schroth et al. 2002; Shepherd and Montagnini 2001). A summary of the above- and belowground C sequestration rates in vegetation reported in some major AFS around the world (Table 20.1) shows that the estimates of CSP in AFS range from 0.29 to 15.21 t ha^{-1} $year^{-1}$. These values are a direct manifestation of the ecological production potential of the systems, depending on several factors including site characteristics, land use types, species involved, stand age, and management practices. Moreover, biomass production may not represent the UNFCCC-stipulated measure of C sequestration ("secure storage in long-lived pools"). Notwithstanding these limitations, in general, AFS on the arid, semiarid, and degraded sites have a lower CSP than those on the humid sites; and, the temperate AFS have relatively lower CSP compared with tropical systems (Nair 2012).

Table 20.1 Mean vegetation (above and belowground) carbon sequestration[1] potential of prominent agroforestry systems[#]

Agroforestry/land use system[2]	Age[3] (yr)	Mean vegetation C (Mg ha^{-1} yr^{-1})	Source
Fodder bank, Ségou, Mali, West African Sahel	7.5	0.29	Takimoto et al. (2009)
Live fence, Ségou, Mali, West African Sahel	8	0.59	Takimoto et al. (2009)
Tree-based intercropping, Canada	13	0.83	Peichl et al. (2006)
Parklands, Ségou, Mali, West African Sahel	35	1.09	Takimoto et al. (2008b)
Silvopasture, Western Oregon, USA	11	1.11	Sharrow and Ismail (2004)
Silvopastoralism, Kurukshetra, India	6	1.37	Kaur et al. (2002)
Silvopastoralism, Kerala, India	5	6.55	Kumar et al. (1998)
Cacao agroforests, Mekoe, Cameroon	26	5.85	Duguma et al. (2001)
Cacao agroforests, Turrialba, Costa Rica	10	11.08	Beer et al. (1990)
Shaded coffee, Southwestern Togo	13	6.31	Dossa et al. (2008)
Agroforestry woodlots, Puerto Rico	4	12.04	Parrotta (1999)
Agroforestry woodlots, Kerala, India	8.8	6.53	Kumar et al. (1998)
Home and outfield gardens	23.2	4.29	Kirby and Potvin (2007)
Indonesian homegardens, Sumatra	13.4	8.00	Roshetko et al. (2002)
Mixed species stands, Puerto Rico	4	15.21	Parrotta (1999)

Notes:
1. Though reported as carbon sequestration potential, the values seem to denote C stock
2. Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species
3. "Age" of the system, though not clearly defined, is assumed to be the number of years since establishment of the tree component in the system
These systems were selected from many reports of this nature to provide a broad spectrum of agroforestry systems (live fences to multistrata systems) in various geographical regions

Given that the aboveground C sequestration estimates are direct manifestations of AGB production, the basic process that drives C sequestration is the same as that for AGB production, i.e., the uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation. Sequestration involves the additional step of "secure storage" of such fixed C, which is influenced by several ecological and management factors (see Section 20.6.2). Belowground C sequestration is influenced by inherent soil properties and processes, some of which are not influenced by management practices. Moreover, as stated above, roughly two-thirds of the total C sequestration occurs below ground. Therefore, belowground (especially soil-related) mechanisms and processes are considered in more detail than the aboveground mechanisms and processes in subsequent sections of this chapter.

20.3.3 Belowground (Soil) Carbon Sequestration

Soils play a vital role in the global C cycle. The soil C pool comprises SOC estimated at 1550 Pg (Gt), i.e., about 5500 Pg CO_2, and soil inorganic C about 750 Pg, both to 1-m depth (Batjes 1996). Other similar estimates are also available (e.g., Sanderman et al. 2017). Any change in the soil C pool would have a significant effect on the global C budget (Smith et al. 2019). The historical amount of CO_2-C emitted into the atmosphere from the terrestrial ecosystems is estimated to be about 136 ± 55 Pg, of which soils account for about 78 ± 12 Pg (Lal 2008). It is known that best management practices can restore at least some of this lost carbon (Lal et al. 2018), so it has been suggested that soil C sequestration could be a significant greenhouse gas removal strategy (also called negative emission technology [NET], or carbon dioxide removal). Soil organic matter (SOM), which contains more reactive organic C than any other single terrestrial pool, plays a major role in determining C storage in ecosystems and in regulating atmospheric CO_2 concentrations. A reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppm (Lal 2001). Loss of organic C from tropical soils not only increases the atmospheric CO_2 content but also reduces the fertility of those soils that are generally nutrient-poor (Nair and Nair 2003). Thus, soil C that traditionally has been a sustainability indicator of agricultural systems has now acquired the additional role as an indicator of soil (environmental) health.

The literature on soil carbon sequestration (SCS) potential of AFS is scanty although rather plentiful reports are available on the potential role of agricultural soils to sequester C. Reviewing the available information on SCS in AFS worldwide, summarized in Table 20.2, Nair et al. (2009a) reported that the estimates varied greatly across systems, ecological regions, and soil types. A general trend of increasing SCS in agroforestry compared to other land-use practices under similar ecological conditions (except for forests) was clear. Overall, the land-use systems were ranked in terms of their SOC content in the order: forests> agroforests> tree plantations> arable crops [agroforests are complex multistrata systems, similar to homegardens in structural complexity, but larger in area: Nair et al. 2009a, b]. The impact of any AFS on soil C sequestration depends largely on the amount and quality of biomass inputs provided by the tree and non-tree components of the system, and on properties of the soils, such as soil structure and their aggregations. Biomass inputs, in turn, are conditioned by alterations in above- and belowground total productivity, modifications to rooting depth and distribution, and changes in the quantity and quality of litter inputs (Connin et al. 1997; Jackson et al. 2000; Jobbágy and Jackson 2000), which modify the C dynamics and storage in the ecosystem (Schlesinger et al. 1990; Ojima et al. 1991). Thus, SCS in AFS is dependent on numerous factors, ranging from agroecological conditions to management practices.

20.3.4 Mechanisms of Soil Carbon Sequestration

The decomposing plant residues and other organic materials in the soil are a source of C and nutrients for the new growth of microbial communities and plants. Much of this C is released back into the atmosphere as CO_2 during respiration or is incorporated into living biomass. However, about one-third of SOM breaks down much more slowly and could still be present in the soil after one year (Angers and Chenu 1997). This SOM represents a significant carbon store and can remain in the soil for extended periods as a part of soil aggregates. The fraction of SOM that is so “protected” from further rapid decomposition is very important for soil C sequestration.

Types of soil organic matter protection. Soil organic matter is protected in the soil by three main processes: biochemical recalcitrance, chemical stabilization, and physical protection (Christensen 1996; von Luetzow et al. 2008). ***Biochemical recalcitrance*** occurs when the chemical make-up of SOM involves aromatic polymers and other structures that are difficult for microbes to break down (Christensen 1996). A common example is lignin, one of the main components of woody plants. However, it is now believed that biochemical recalcitrance must work in conjunction with other factors such as physical protection and organomineral stabilization (Flessa et al. 2008; Marschner et al. 2008). ***Physical protection*** is the binding of SOM in soil aggregates, separating it from microbial populations and preventing its degradation, such that fractions of SOM that would otherwise be labile are not exposed to microbial activity and can remain in the soil for much longer periods (Six et al. 2000). However, the eventual shifting and breaking of aggregates lead to the exposure and subsequent breakdown of this protected SOM. ***Organomineral stabilization*** is the conversion and binding of SOM with minerals to form organomineral complexes that can remain in the soil for extended periods; in conjunction with physical protection and biochemical recalcitrance, it helps to create stable SOC. The majority

Table 20.2 Some reports on soil carbon sequestration potential[1] under agroforestry systems[#]

Agroforestry system/ Species[2]	Location	Age (yr) [3]	Soil depth (cm)	Soil C (t ha^{-1})	Reference/ Comments
Mixed stands, *Eucalyptus* +*Casuarina, Casuarina* + *Leucaena* and *Eucalyptus* + *Leucaena*	Puerto Rico	4	0–40	61.9, 56.6, and 61.7	Parrotta (1999)
Agroforest: *Pseudotsuga menziesii* + *Trifolium subterraneum*	Western Oregon, USA	11	0–45	95.89	Sharrow and Ismail (2004)
Agrisilviculture (*Gmelina arborea* + eight field crops)	Chhattisgarh, Central India	5	0–60	27.4	Swamy and Puri (2005)
Tree-based intercropping: hybrid poplar + *Hordeum vulgare*	Ontario, Canada	13	0–20	78.5	Peichl et al. (2005)
Silvopastoral system: *Acacia mangium* + *Arachis pintoi*	Pocora, Atlantic coast, Costa Rica	10–16	0–100	173	Amézquita et al. (2005)
Silvopastoral system: *Brachiaria brizantha* + *Cordia alliodora* + *Guazuma ulmifolia*	Esparza, Pacific coast, Costa Rica	10–16	0–100	132[a]	Amézquita et al. (2005) Stable C =14 Mg/ha
Alley cropping *Leucaena*-4 m	Western Nigeria	5	0–10	13.6	Lal (2005)
Alley cropping: hybrid poplar + wheat, soybeans (*Glycine max*) and maize rotation	Southern Canada	13	0–40	1.25	Oelbermann et al. (2006)
Alley cropping system: *Erythrina poeppigiana* + maize and bean (*Phaseolus vulgaris)*	Costa Rica	19	0–40	1.62	Oelbermann et al. (2006)
Shaded coffee, *Coffea canephora* var *robusta* +*Albizia adianthifolia*	Southwestern Togo	13	0–40	97.27	Dossa et al. (2008)
Agroforest (home and outfield gardens)	Ipetı´-Embera, Panama		0–40	45.0 ±2.3	Kirby and Potvin (2007)
Faidherbia albida parkland	Ségou, Mali	35	0–100	33.3	Takimoto et al. (2009)
Live fence (*Acacia nilotica, A. senegal, Bauhinia rufescens, Lawsonia inermis, and Ziziphus mauritiana*)	Ségou, Mali	8	0–100	24	Takimoto et al. (2009)
Fodder bank (*Gliricidia sepium*, *Pterocarpus lucens* and *P. erinaceus*)	Ségou, Mali	6–9	0–100	33.4	Takimoto et al. (2009)
Tree-based Pastures: slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*)	Florida, USA	8–40	0–125	6.9 to 24.2	Haile et al. (2008)

Notes:
1. Though reported as carbon sequestration potential, the values seem to denote C stock
2. Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species
3. "Age" of the system, though not clearly defined, is assumed to be the number of years since establishment of the tree component in the system
These systems were selected from many reports of this nature to provide a broad spectrum of agroforestry systems (live fences to multistrata systems) in various geographical regions

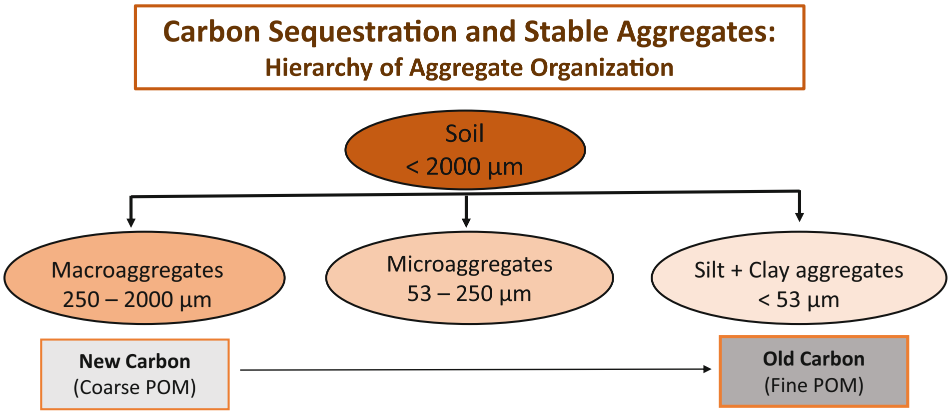
of recalcitrant SOM is bound in organomineral complexes; Mikutta et al. (2006) found that at least 86% of SOM was mineral-protected in forest subsoils. Physical protection and biochemical recalcitrance can allow SOM to remain in the soil longer, giving time for the formation of organomineral complexes. Thus, the recalcitrance of SOM is a combination of these short- and long-term processes, in which soil aggregates play a major role (Six et al. 2004).

20.3.5 Soil Aggregates and Their Importance in Soil Carbon Sequestration

Aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic substances (Jastrow and Miller 1997; Bronick and Lal 2005). They range in size from microns to millimeters and are often classified according to their ability to resist slaking in water. Depending on their diameter, they are classified into macroaggregates that are 250 – 2000 μm in diameter, and microaggregates that are smaller than 250 μm in diameter. The smallest size fractions (smaller than 53 μm in diameter) among the microaggregates are referred to as the silt+clay fraction, which is bound together in larger microaggregates and are held together with polysaccharides and humic materials that are fairly persistent due to biochemical recalcitrance and physical protection. These three size classes occur in what is referred to as an aggregate hierarchy. The largest aggregates, the macroaggregates, are least stable and break up most easily when exposed to slaking. These are followed by the intermediate-sized microaggregates, which are slightly stronger than the macroaggregates and, finally, the smallest microaggregates which are the most stable (Tisdall and Oades, 1982). The age and amount of C in each size class also follows this aggregate hierarchy: the highest concentration of C is in the macroaggregates. This C is also, on average, the youngest. The lowest concentrations of C and the oldest C is in the smallest fractions or microaggregates including silt + clay. Different procedures are available to divide SOM into several fractions based on the degree of physical protection and occlusion within aggregates (Cambardella and Elliott 1994; Golchin et al. 1994; Sollins et al. 1996; Swanston et al. 2002). Elliott (1986) fractionated SOM into decomposable and recalcitrant fractions based on its location within aggregates of different sizes. Aggregates physically protect SOM by (1) forming a physical barrier between microorganisms, microbial enzymes, and their substrates, (2) controlling food web interactions, and (3) influencing microbial turnover (Six et al. 2000). The inclusion of organic materials within soil aggregates reduces their decomposition rate (Oades 1984; Elliott and Coleman 1988). Increases in aggregation concomitant with increases in organic C have been observed in no-till systems (Paustian et al. 2000; Six et al. 2000).

Aggregate Formation and Stabilization Aggregates are stabilized when large macroaggregates form from a combination of older microaggregates and freshly added SOM (Figure 20.2). Many of the compounds in fresh SOM are physically protected within the macroaggregate, but they readily decompose if exposed. If the macroaggregate remains intact, over time, this fresh organic matter is converted through a combination of microbial activity and abiotic factors to recalcitrant organomineral complexes. This eventually leads to an increase in the concentration of recalcitrant microaggregates within macroaggregates, increasing the amount of C sequestered in the soil. Macroaggregates only have a life span of a few years compared to decades for microaggregates, but the stability for this period is closely linked with the conversion of fresh SOM into recalcitrant microaggregates (Puget et al. 2000). Thus, in the process of C sequestration, the formation of microaggregates (<250 μm), where the oldest and most recalcitrant SOC is found, hinges on the formation and stability of macroaggregates and the availability of fresh SOM.

The "glue" that holds macroaggregates together results from biological activity surrounding fresh SOM, which consists of plant residues that still have a recognizable cell structure and are referred to as coarse intra-aggregate particulate organic matter (iPOM) (Kogel-Knabner et al. 2008). Soil aggregates are often formed by microbial activity centered around coarse iPOM (Oades and Waters 1991; Golchin et al. 1994). In the process of breaking down iPOM, microbes deposit polysaccharides and other chemicals that act as binding agents in the soil, which stick mineral particles and



	Macroaggregates	Microaggregates	Silt + Clay
Size (μm)	250 – 2000	53 – 250	< 53
MRT of C (years)	1 – 10	10 – 100	> 100
Enzyme activity	High	Medium	Low
Binding agents	Fungal hyphae, fine roots, microbial residues	Microbial polymers, root exudates, polyvalent cations	Organomineral complexes
Management effects	High	Medium	Low

Figure 20.2 A schematic drawing of the formation and hierarchy of soil aggregates

microaggregates together, giving structural integrity to the macroaggregate. This also reduces air and water movement, creating anoxic conditions and slowing down microbial activity and decomposition of SOM within the macroaggregate. Roots and hyphae grow around the iPOM, further physically protecting and stabilizing the macroaggregate (Oades and Waters 1991). Hyphal exudates from arbuscular mycorrhizal fungi such as glomalin are closely linked with aggregate stabilization. They are found in high concentrations in the soil, have high recalcitrance, and often form coatings on soil aggregates even after hyphae have senesced. Exudates produced by roots can also help in the physical and chemical binding of smaller microaggregates into larger macroaggregates. Macroaggregate formation is dependent on a combination of products of these microbial communities, roots, and hyphae. Carbon to nitrogen (C: N) ratios in SOM affect biochemical recalcitrance against microbial activity and, subsequently, rates of decomposition. Furthermore, organic matter high in lignin and other large molecules made of complex aromatic amorphic carbon structures are difficult for microbes to break down (Chapter 16, Figure 16.4) 16.4) and can remain intact in the soil for longer periods Section 16.2. In the short term, materials high in sugars and proteins are broken down more quickly. Thus, biochemical recalcitrance can allow SOM to remain longer, giving it a chance to form organomineral complexes. This means that over time, coarse iPOM is broken down into fine iPOM. Coarse iPOM is much more susceptible to decomposition while fine iPOM binds with mineral particles and microbial products and forms more recalcitrant SOC (Six et al. 2000). Thus, management practices that favor the building and maintenance of soil macroaggregates are important to the recalcitrance of iPOM and its incorporation into microaggregates.

Factors Affecting Soil Aggregate Formation: Soil type, climate, landscape position, ecology, and anthropogenic factors all play a major role in aggregate formation and soil carbon sequestration (Christensen 1996). In the context of the discussion on the impacts of agroforestry on carbon sequestration, it is important to understand the role of these environmental factors in soil aggregate formation. Besides, the variability in results from site-specific studies can be better understood and their broader implications ascertained in light of the effect of these environmental factors.

Soil Texture. Soil texture plays a large role in the number and kind of primary organomineral complexes that are formed (Christensen 1996). Clays form the majority of complexes with organic C and can greatly enhance aggregation and the stability of those aggregates. Also, clay is closely positively correlated with the physical protection of SOM (Hassink and Whitmore 1997), and with SOC in the soil (Jobbágy and Jackson 2000). The importance of clay in SOC content in soil increases with soil depth, playing a larger role than the climate in deeper horizons (Jobbágy and Jackson 2000). Besides, clayey soils tend to aggregate due to the wet–dry cycles as a function of the mineral properties (Horn and Smucker 2005). Therefore, soils that have high clay content exhibit strong aggregate formation and stability and follow classical models of aggregate hierarchy (Figure 20.2). On the other hand, sands do not form organomineral complexes and must rely on the physical binding of roots, hyphae, and related OM for aggregate formation. Thus, the aggregates that are formed in sandy soils such as Spodosols are typically weak although they do still exhibit aggregate hierarchy (Sarkhot et al. 2007). The movement of SOC down the soil profile to the Bh horizon also occurs in Spodosols, and C is sequestered deeper in the soil profile (Sarkhot et al. 2007).

In addition to texture, other factors that are important to aggregate formation and stability are similar to those that determine soil quality, including a combination of aeration, soil moisture, flora and fauna, climate, and organic matter inputs. Reactive properties of the minerals making up the soil can also play an important role in aggregate formation. When the key binding factors are oxides instead of organic matter, such as in Oxisols, soil aggregation is dictated by completely different physical and chemical processes. Soils other than Oxisols have higher levels of SOC in macroaggregates than in microaggregates because microaggregates are bound together by organic matter in the macroaggregate. However, oxides are the major binding agent in Oxisols, and they do not display this same framework of organic matter build up. Climatic factors such as temperature and humidity greatly affect the activity of microbial communities and the breakdown of organic matter in soil aggregates. Cold or dry climates slow down processes leading to a slower rate of aggregate formation and breakdown. On the other hand, moist and/or warm climates have very high microbial activity leading to a faster turnover of organic matter in the soil. Although moist climates have higher microbial activity, very wet climates can have anoxic (anaerobic) soil conditions, leading to little organic matter breakdown. Thus, cooler and wetter climates have a greater potential to sequester carbon than dry and hot climates (Lal 2006). Nitrogen fixation and mycorrhizal associations can increase nutrient availability, boosting microbial populations, resulting in higher levels of SOC and aggregate stability (Haynes and Beare 1997). Moreover, different plant species produce different types and amounts of plant residues affecting the total amount of SOM as well as the type and the ability of microorganisms to break it down. Woody, deep-rooted plants can increase the amount of SOM and microbial activity deep within the soil profile compared to shallow-rooted grasses (Jobbágy and Jackson 2000; Liao et al. 2006; Haile et al. 2008).

Although soil aggregates and size fractions have an important effect on the retention of C in soil and environmental factors play an important role in the aggregate formation, information on these topics under AFS is scanty. Udawatta et al. (2008) reported that in an Alfisol in Missouri, USA, the agroforestry buffer treatment had more water-stable aggregates than the grass-buffer and row-crop treatments at 0–40 cm soil depth. Results of a series of multi-locational (multi-country) studies conducted on different AFS by the Agroforestry Program of the University of Florida, Gainesville, FL, USA, during the past two decades (2000–2019) showed wide variations in the distribution of aggregate-size fractions in different soils. These results are summarized separately in Section 20.5.1.

20.4 Measurement and Estimation of Carbon Sequestration in Agroforestry Systems

This section reviews the various methods employed in measuring and estimating C sequestration in AFS and the lessons learned. Although the words measurement and estimation are used rather loosely and interchangeably, there are subtle differences between the two. Most estimations are based on some quantitative measurements in the fields and laboratories. When the results of such measurements are reported almost directly without too much extrapolation, they are considered as measurements. When the measured quantity or parameter is extrapolated with the input of other factors and parameters to represent a broader area or entity than the unit of measurement, it is an approximation or estimate. For example, the value of the C content of a soil obtained from laboratory analysis of a soil sample represents a measurement. Several such values may then be used along with other relevant measured or assumed values to project, often with the help of computer models, the C stocks, and dynamics (changes with time) of larger regions; these will be estimates. The aboveground values of C sequestration on a plot or field are mostly direct derivatives of biomass measurements and the estimates based on them are relatively more accurate and straightforward, whereas estimates of belowground (soil) C stock over large areas (such as regional-, country-, and global levels) are more complex and relatively less accurate and precise.

20.4.1 Vegetation

Aboveground measurement of carbon stock involves summing up the amount of harvested and standing biomass. Estimation of tree biomass by whole-tree harvesting is an age-old approach. Nair (1979) used that procedure for estimation of coconut (*Cocos nucifera*) biomass: cutting down sample trees, separating various parts (stem, leaves, inflorescence, etc.), digging out and washing the roots, determining their dry weights from samples of each part, and adding them up to get the total biomass. Parrotta (1999) estimated the tree biomass and C content in Panama. After dividing up the harvested representative trees into their various components (branchlets, branches, dead branches, leaves, roots, and fine roots), C content in each component was measured by the combustion of the samples. The whole tree biomass and carbon content so derived were then used to develop a regression curve. Several other whole-tree-harvest studies of a similar nature have also been reported. These are extremely time- and labor-intensive. General allometric equations (FAO 2007; Piccard et al. 2012) that are widely used in forestry (e.g., Alvarez et al. 2012; Chaye et al. 2014), and recommended by UNFCCC (2007) for tree-biomass estimation of tree biomass, have been used in agroforestry situations too. For example, Takimoto et al. (2008) used such general allometric equations (in the absence of species-specific equations) for estimating standing tree biomass in the parkland agroforestry systems in the Sahel. In other cases, more simple analyses were used for large-scale estimations. Dixon et al. (1993) made estimations by measuring the volume of stem wood and multiplying it with species-specific wood density; that number was then multiplied by 1.6 to get an estimation of whole-tree biomass. In all these cases, C content was assumed to be 50% of the estimated whole-tree biomass, and root biomass was excluded often.

Besides the concerns about the accuracy of these estimates, destructive sampling procedures for C and biomass determinations can be difficult for smallholder agroforestry plots, which constitute much of the agroforestry in developing countries. Agroforestry in many developing countries involves a multitude of plants of varying growth habits yielding diverse economic products. The species are planted, and their products harvested, mostly for household consumption, throughout the year, with no defined planting and harvesting schedules. Variations in tree management can be another issue: trees in AFS may be pruned depending on management objectives or may have different growth forms due to differences in spacing compared to natural (forest) systems. Furthermore, no two agroforestry plots are similar: each may be unique in terms of plant composition, planting arrangements, and stand densities. Thus, the determination of biomass production from indigenous AFS is a challenging task and makes extrapolation from one system to others difficult and sometimes unrealistic (see Section 20.4.3).

20.4.2 Belowground (Soils)

The determination of belowground organic carbon dynamics in agroforestry systems is crucial for understanding the impact of the system on C sequestration, but it is difficult. Organic C occurs in soils in different forms, including living root and hyphal biomass, microbial biomass, and SOM in labile and recalcitrant forms. The complex interactions of these different forms make the measurement, estimation, and prediction of soil C sequestration a daunting task. Methods that have been used for assessing the content and attributes of SOC will be briefly reviewed here.

Soil organic C is often measured on a whole-soil basis. The Walkley-Black procedure, employed extensively in the past, involves the digestion of organic matter in the sample through oxidation with potassium dichromate. The digestion is incomplete, ranging from 60% to 87% depending on the sample (Walkley 1947); therefore, an average correction factor of 1.33 is applied. This could lead to overestimations or underestimations depending on the soil. Moreover, the use of potassium dichromate makes the technique less environment-friendly. Because of these concerns, the procedure has since been abandoned (Kimble et al. 2001). However, most of the earlier data (before the 1990s), and even some since then, are based on that method.

Currently, many studies measure SOC by quantifying the amount of CO_2 produced through heating in a furnace. Other studies measure the change in weight of the sample after heating. However, the temperature used can vary; it needs to be standardized for accurate comparison of different studies. The presence of carbonates and charcoal in the soil can also skew results (Kimble et al. 2001). These measurements of C on a whole soil basis give information about total concentrations, but other analytical procedures are needed to determine details of the form and recalcitrance of the stored C as well as where it is stored. Various analytical methods used for the determination of soil carbon content in agricultural soils at the field-, landscape-, and regional levels were reviewed recently by Nayak et al. (2019).

Measurement of Soil Aggregates: As explained in Section 20.3.5, the study of soil aggregates is critical to SCS determinations. Most soil aggregation studies use some adaptation of the wet sieve method. It involves putting the soil in the top of a nest of sieves and lowing and raising the sieves in water to simulate the natural wetting of the soil. The different aggregate classes then break down and are caught in different levels of the sieve. This technique has been widely used and is easy to replicate. The wet sieve method has been carried out successfully for a range of soil types including Alfisols, Inceptisols, Mollisols, Oxisols, Spodosols, and Ultisols (Filho et al. 2002; Haile et al. 2008; Oades and Waters 1991; Six et al. 1998; Williams and Petticrew 2009). Usually, the recovery rate of the sum of aggregates compared to the whole soil is high. For instance, Haile et al. (2008) had a recovery rate of 97.5% suggesting minimal loss caused by methodology on aggregate size fractions.

Measurement of the proportion of soil microaggregates within macroaggregates can give important information about the quality of the macroaggregate and the amount of SOM it is protecting (Nair et al. 2010). The technique developed by Six et al. (2000) is a commonly used one. Six et al. (1998) also derived a method to isolate particulate organic matter (POM) in the whole soil and within aggregates, and it is a valuable measurement for determining the amount of fresh organic matter in the soil and within aggregates. The procedure involves isolating the POM that is not occluded and then breaking up aggregates to find the iPOM (see under *Aggregate Formation and Stabilization,* Section 20.3.5). The aggregates are flocculated and run through a nest of sieves, with any particulate matter that is larger than sand, silt, or clay isolated. It is also a way of separating measurements of mineral associated SOM from iPOM. Because iPOM can comprise a large fraction of the organic matter in an aggregate, this is an important way to get better estimates of the more recalcitrant forms of broken-down and mineral- associated SOM. Sand corrections have also become an important addition to making accurate C and N measurements of aggregates (Elliott et al. 1991). Because sand grains do not have any organic matter, they must be excluded from the measurements of OM in that size class. The amount of organic matter found in each aggregate size class can be found using sonication (Cambardella and Elliott, 1993); some additional measurements of this nature have been reviewed by Nair et al. (2010).

Since the majority of SOC is found in soil aggregates, we can have a better understanding of how carbon is entering, moving through, and leaving the soil by understanding the structure and cycling of these aggregates. Previously, many studies have looked at SOC on a whole soil basis. Although that gives us a general understanding of the amount of carbon being sequestered and its residence time in the soil, understanding the aggregates will give us the ability to predict future levels based on inputs and current conditions. By knowing what factors are likely to influence aggregate formation and stability, we can predict what factors to take into consideration. We will thus be able to better develop and adopt new agricultural and land management practices to optimize carbon sequestration both immediately and for the long term.

Measurement of Belowground Living Biomass: In addition to SOM, belowground net primary productivity (biomass) is a major C pool (Nadelhoffer and Raich 1992). However, belowground biomass is difficult to measure. The root-to-shoot ratio is therefore commonly used to estimate belowground living biomass. The ratios differ considerably among species and across ecological regions. These difficulties pose a serious problem in our understanding of belowground C sequestration in living biomass. Allometric equations for predicting root biomass have also been constructed, but are not yet popular. Living microbial biomass can be an important indicator of organic matter decomposition and turnover too. There are myriad procedures for gaining a detailed understanding of the make-up of microbial populations, but they are often complicated and give more detail than is needed for the basic understanding of microbial activity and biomass. Common measurements include chloroform fumigation (Vance et al. 1987) and adenosine triphosphate (ATP) assays (Williams and Petticrew 2009).

Isotope Measurements and Carbon Dating: Numerous studies (Accoe et al. 2002; Bernoux et al. 1998; Ehleringer et al. 2000; Swap et al. 2004) have used stable C isotope-ratio analysis to trace the source of SOC to plants that follow C3 and C4 photosynthetic pathways. The reported δ^{13}C values range from −19 to −9‰ for C4 plants and −35 to −20‰ for C3 plants (Biedenbender et al. 2004; Staddon 2004). When a C4 plant is introduced to a system that had previously been under a C3 plant or vice versa, the relative contribution of new vs. old soil organic C can be quantified using the mass balance of stable isotope contents based on the change in ^{13}C signature of SOM (Dawson et al. 2002; Del Galdo et al. 2003). In a combined tree + grass land-use system, C3 inputs are dominated by either woody shrubs or trees and C4 inputs are dominated by grass (McClaran and McPherson 1995). The $\delta^{13}C$ isotope technique requires a comparison between a site where the photosynthetic pathway of the dominant vegetation (C3 or C4) has been changed and a reference site where the photosynthetic pathway of the vegetation remains unchanged. Haile et al. (2010) used that technique in silvopasture systems of the southeastern USA, composed of slash pine (*Pinus elliottii*), a C3 plant, $\delta^{13}C \approx -29.5$ ‰, with bahiagrass (*Paspalum notatum*), a C4 plant, $\delta^{13}C \approx -13.3$‰, as the understory species. Combining SOM fractionation techniques with the ^{13}C natural abundance technique offers a compelling approach to investigating small shifts in soil C stores that would be significant in the long term but might not be detected by conventional methods.

Carbon 14 (^{14}C) dating can be used to determine the age of SOM. When a plant incorporates carbon from CO_2 in the atmosphere, it takes in an amount of ^{14}C proportional to the amount in the atmosphere. However, once the organism dies, the amount of ^{14}C slowly decreases at a fixed rate due to radioactive decay. Ages of carbon in the soil can thus be determined (Kaiser et al. 2002). The contribution of fossil carbon compared to the organic matter in soil aggregates can also be determined using ^{14}C dating (Flessa et al. 2008; Rethemeyer et al. 2004). Carbon dating can also be used to track the recalcitrance of different SOM fractions. Due to nuclear weapons testing, there was a sharp increase in atmospheric ^{14}C starting in 1954 and spiking in 1963. This spike, referred to as bomb-^{14}C, can be used as a benchmark for measuring the age of SOC (Rethemeyer et al. 2005). Other studies have used ^{14}C labeling of plant roots or other organic matter inputs to determine the mechanisms and location of organic matter incorporation into soil aggregates (Gale et al. 2000). Measurements of ^{14}C in different aggregate fractions can then be used to track the decomposition and incorporation of the roots. From a study using ^{14}C in agroforestry combinations of *Eucalyptus* spp. with fodder grass (*Panicum* spp.) or rice (*Oryza sativa*) as understory species in the Oxisols of Minas Gerais state, Brazil, Tonucci et al. (2017) reported that, at 50–100 cm soil depth, the silt + clay fraction (<53μm) had higher (negative) values of $\delta\ ^{14}C$ than the 53–250 and 250–2000 μm fractions (range of $\delta\ ^{14}C$ values: -348.3 to -257.2; Table 20.3). The positive $\delta\ ^{14}C$ values in the surface 0–10 cm soil indicated that the organic matter in the surface soil was of recent formation, and that the mean residence time of SOC was greater at the lower depth and in the most stable fraction (<53μm) of this AFS.

Spectroscopic Analysis: Some advances have been made in the use of Infrared spectroscopy (IR) to determine spectral indicators of soil fertility that can directly be calibrated to soil and

Table 20.3 Radiocarbon dating of total soil at different depth of three land-use systems: pasture, forest, and old agroforestry (OAF; site established in 1985, soils sampled in 2008)

Site	Fraction (μm)	Depth (cm)	$\Delta^{14}C$ (‰)	^{14}C age (BP)
Pasture	Whole soil	0 – 10	−45,5±1,2	315
		50 – 100	–262,5±1,0	2390
Forest	Whole soil	0 – 10	73±1,4	Modern
		50 – 100	–251,3±0,9	2270
OAF	Whole soil	0 – 10	0,5±1,2	Modern
		50 – 100	–234,3±0,9	2085
OAF	250 – 2000	50 – 100	–270,8±1,0	2480
	250 – 53	50 – 100	–257,2±0,9	2330
	<53	50 – 100	–348,3±0,8	3385

Adapted from Tonucci et al. (2007)

crop responses to management and thus by-pass the need for conventional soil tests (Shepherd and Walsh 2007; Nocita et al. 2014). The shape of the infrared spectra obtained in a 30-second measure that requires no chemicals will characterize the basic molecular structure of the mineral and organic composition of the soils that determine the soil's functional properties such as the amounts of SOC in different pools, soil's structural stability, and erodibility, ability to retain and supply different nutrients and water, and nitrogen mineralization characteristics. The procedure has been used to predict various soil C fractions and their mineralization rates in soils of Australia and Kenya (Janik et al. 2007). In support of these approaches, ICRAF has established a unique Soil-Plant Spectral Diagnostic Laboratory that analyses soils using only light (infrared, x-ray, laser) with the capability for total elemental analysis in soils, plants, and water (Vågen et al. 2012; Van Noordwijk 2019). These technological advances could help hasten the transformation of the traditional, hoe-and-machete-based agroforestry to its modern version using handheld, mobile-phone-based spectrometers, and other technological marvels.

Modeling: Computer models are increasingly being used for understanding the rates of terrestrial carbon cycling, in general. They are based on a collection of assumptions based on the ecological processes, including tree growth and decomposition processes in the soil. Some such efforts are also being made, though to a limited extent, in agroforestry systems.

The most widely used soil carbon models are the CENTURY and RothC. The former, originally developed for grassland soils by Parton et al. (1987), predicts long-term soil C cycling and SOM decomposition for forest and agricultural lands. It models the cycling of C and other elements (phosphorus, nitrogen, and sulfur) and their interactions, focusing specifically on the effects of species type and management practices such as tillage to model agricultural systems. It accounts for agricultural systems, forests, or savannas. Although seldom used for integrated systems such as agroforestry, one study has reported its use to model an agroforestry system (Russell and Kumar 2019). The Rothamsted model (RothC model) was developed based on the long-term experiments studying organic matter on the Rothamsted sites in England for agricultural, forestry, and grassland systems. It takes climate, management, and soil type into consideration, and soil data are used for calibration (Jenkinson 1990). Although the parameters of the model are comparatively simple, they are surprisingly good at modeling the breakdown of organic matter at the site. With slight modification to the decomposition rate of the resistant plant material pool and the humic pool, the model was accurate when compared to measured field data in Australia (Skjemstad et al. 2004). However, the model may not be as appropriate for predictions of tropical agroforestry sites; for example, decomposition rates were greatly underestimated when RothC was applied to an agroforestry system in Nigeria (Diels et al. 2004).

The G'DAY is an ecological model based on the CENTURY model that is used to predict the effects of elevated CO_2 and raised temperature on ecosystems. Medlyn et al. (2000) used this model to determine the important role that soils play in the long-term net primary productivity. The APSIM (Agricultural Production Systems Simulator) model is also used commonly although it is more focused on crop production and yields in terms of soil conditions (McCown et al. 1996). An ecosystem-level model used for alternative management practices that estimate total C sequestration is the CO2FIX (Masera et al. 2003). It is applicable to temperate and tropical systems and takes into account forest stands, dead wood, and soil carbon. It is used for the estimation of uneven-aged or multi-cohort systems such as selectively cut forests or agroforestry systems. This model differs from CENTURY and RothC because it only takes into consideration very recalcitrant soil C or labile C, without any intermediate forms, based on the assumption that the time step of this model is one year, within which period the intermediate forms of C do not make a difference.

Another model that though not focused on carbon sequestration *per se* could be a valuable tool is the yield-SAFE model, developed to assess the environmental and economic impact of agroforestry in Europe (van der Werf et al. 2007). It involves the input of only basic parameters such as temperature, precipitation, soil type, and species selection and spacing, and gives information about yields and effects on erosion and other environmental factors. Because it was designed for use in agroforestry systems, it differs from other described models that were developed for forests or agricultural land, and it could be a useful tool to be integrated into carbon modeling for agroforestry systems. Some improvements to this model have since been suggested.

Some characteristics of these common models, including recent (since 2010) improvements to the earlier models are summarized in Table 20.4. To get ecosystem estimates, these soil carbon models must be incorporated into larger ecosystem models. The information required for the model must then be easily attainable, and the model must run at the same time-step as the other aspects of the ecosystem-level model. In conclusion, as far as the application of modeling to soil C and other aspects of agroforestry systems are concerned, the path to traverse is rather long.

20.4.3 Methodological Difficulties

A uniform set of methods and procedures has, unfortunately, been not yet developed for measuring and/or estimating C sequestration in agroforestry systems. Consequently, the methods followed are not uniform and often may have serious drawbacks. Wide variations exist in the procedures used in all aspects such as sampling, analytical methods, computations, data interpretation, and presentation. Naturally, this can greatly affect the conclusions made when comparing the differences under various management practices, soils, environments, and social conditions. Many of these difficulties are common to other land-use systems too. The major weaknesses and deficiencies related to carbon sequestration studies in AFS, described by Nair (2012), are summarized below.

The Concept of Carbon Sequestration: The "long-lived pool" of carbon that is referred to in the UNFCCC definition of C sequestration (*the secure storage C (CO_2) that is removed from the atmosphere in long-lived pools*)" has created some confusion in determining what "sequestered C" is. Most reports on C sequestration in land-use systems, especially AFS, are based on C-stock computations, in which aboveground biomass is estimated from some arbitrarily chosen or overly general allometric equations. Belowground biomass is considered as a fraction; usually, 30% of the aboveground biomass (AGB), and 50% of the total biomass is taken as C stock (and sequestered C). Some reports do not specify if belowground biomass is factored into the estimations. In the case of soil, the C content (as determined by soil analysis and then extrapolated to a region or country) is expressed as C stock and reported as sequestered C. These estimations and computations of C stock in AFS are, therefore, approximations.

Erroneous Assumptions: All estimates may have deficiencies and inadequacies arising from the assumptions used as well as the procedures adopted. Some of the errors that are likely to be common in carbon sequestration studies include the following:

- "*Carbon content in biomass is 50%.*" It is not exactly 50% (although close to it).
- "*All biomass represents sequestered C.*" No, all components of biomass will not end up in "long-lived" pools; for example, when the foliage, which is a part of the biomass, falls on the ground, it decomposes and releases CO_2 back to the atmosphere
- "*Tree biomass (and C) estimates based on existing equations apply to agroforestry situations.*" Such estimates are based mostly on trees growing in plantations or natural stands. These estimates are not directly applicable to open-grown (widely spaced or

Table 20.4 A summary of computer models used in soil-carbon-related studies in agroforestry systems†

S. No	Name of the Model	Nature of studies	AFS studied	Key Features	Drawbacks	Scale of application	References
1	APSIM (Agriculture Productions Systems Simulator)	Soil C in agri. systems; reportedly reliable for soil C predictions	Alley cropping: (Maize with *Gliricidia sepium*	Use of a canopy feature in the model to represent tree-crop interactions	Used for only a limited number of tropical species	Plot scale	Keating et al. (2003); Holzworth et al. (2018); Luedeling et al. (2016); Dilla et al. (2018)
2	APSIM next generation		Alley cropping	Separate Agroforestry module within the model	Unavailable for tropical crops and trees.	Plot- and regional	Smethurst et al. (2017)
3	ECOSSE/ELUM ECOSSE	Poplar (*Populus* spp.)-based agroforestry and other land use changes such as conversion of grassland and forests to temperate-zone agri. crops.		Pool-based approach with C and N transferred between pools.	Restricted to temperate soils (so far); not tested in tropical regions.	Plot- and regional	Pogson et al. (2016); Richards et al. (2017)
4	CO2FIX	Can simulate C dynamics of single or multiple species, and trees of different ages.	Poplar agroforestry	Wide applicability from degraded grasslands to multiple forest ecosystems	Difficult to collect input data on tree / crop components for model validation	Plot scale	Panwar et al. (2017)
5	SCUAF (Soil Changes Under Agroforestry)	Non-growth model for soil carbon; used for alley cropping. Input of relative areas under trees and under crops possible; separate modelling of soil changes for soil-under-trees and soil-under crops;			Does not include precipitation parameter	Non growth model	Young et al. (1998); Grist et al. (1999); Lojka et al. (2007)
6	ICBM/N	Non growth models for soil carbon	Alley cropping	Applicable for different land-use changes	Limited publications, limited use of tropical perennials used in agroforestry	Non growth model	Salazar et al. (2011)
7	Coffee AGROFOR ESTRY MODEL	Plot-scale models of tree and crop growth	Shaded perennial systems	Includes sub model for coffee under shade	Limited use-history, limited published research.	plot-scale	van Oijen et al. (2010)
8	Hi-sAFe or STICS[2]	Plot-scale models of tree and crop growth	Mostly temperate agrofor. Systems	explores planting patterns, tree management, and responses to environmental variables	Complex interactions in silvopasture are not included	plot-scale	Dupraz and Lecomte (2019); Artru et al. (2017)

9	WalNulCAS	Plot-scale models of tree and crop growth	Parkland agroforestry	Well calibrated model for dryland cropping systems	Overestimates the crop performance for biomass	plot-scale models	Coulibaly et al. (2014);
10	Yield-SAFE	The main outputs are the growth dynamics and yields of trees and crops	Silvoarable pasture, Poplar agroforestry	Seven state equations expressing the temporal dynamics of key growth parameters	Not calibrated for tropical agroforestry systems	plot-scale models of tree and crop growth	van der Werf et al. (2007)
11	HMPTrop		Multispecies cropping systems	Designed for soil C estimation in tropical climate on tropical peat development.	Specific to peatlands	plot-scale models of tree and crop growth	Kurnianto et al. (2015)
12	ALWAYS (Alternative land-use with Agroforestry systems)	Management-oriented model. It specifically	Silvopasture	Management decision in the model linked to biophysical equations.	More suitable for temperate and Mediterranean than tropical climates	plot-scale models of tree and crop growth	Balandier et al. (2003)
13	CENTURY	Process-based model of plant–soil nutrient cycling	Multispecies/ Homegarden	Highly precise in soil C modeling. Specialized in simulating biogeochemical processes	Depends highly on input/ litter qualities and does not take specific management practices in to consideration	plot scale models of tree and crop growth	Russell and Kumar (2019)

†This table was compiled by Nilovna Chatterjee, University of Nebraska-Lincoln, USA

scattered) agroforestry trees that could be different in their growth form

- "*All C in soil represents sequestered C*." Only a small percentage of the biomass-derived C that is added to the soil surface contributes to the stock of stable C in soil because the biomass added through litterfall and external additions is subject to rapid decomposition and release of CO_2. If the soil C stock increases over time, that represents the sequestration
- "*Carbon stock is the same as C sequestration*." C stock (t ha^{-1}) does not have a time factor; C sequestration is a rate process involving the time factor (e.g., t C ha^{-1} yr^{-1}).
- "*Growth form of trees has little to do with root biomass*." Estimations of root biomass can vary depending on the differences in growth forms of trees and management practices
- "*The amount of C sequestered is generally uniform for a given agroforestry practice*." No. There can be considerable spatial heterogeneity among similar agroforestry practices at different locations; extrapolation across systems and locations can be misleading.

Operational Inadequacies and Inaccuracies: The lack of uniform methods for estimating the area under agroforestry (Nair et al. 2009a; Udawatta and Jose 2011) poses a major difficulty in reporting C sequestration data under agroforestry systems. Some progress has been made in resolving this puzzle in the tropics (Zomer et al. 2009, 2016), but no such progress seems to have been made in assessing the area under agroforestry in the temperate region. Additionally, there are a few common challenges, primarily in soil-related estimates. For example, soil depth: most soil studies are limited to the surface soils to 20- or 30-cm depth, but tree roots extend to deeper soil horizons. Moreover, the subsoil (below 30 cm depth) has a major role in the long-term stabilization of C. The lack of uniformity in breaking points between soil-horizon depths is another problem: the results of a C study in the 0–5 cm surface horizon cannot be meaningfully compared with those of a 0–50 cm study. Other problems of a statistical nature related to field sampling for soil analyses (such as pseudoreplication and repeated measures) discussed by Nair (2012) are relevant to C sequestration studies too. Another issue is the lack of standardized chronosequence studies that are needed to understand the change in C. Since changes in C stock are unlikely to be linear through time, the nature of the C storage curve over time needs to be examined to understand the periods when most C is being sequestered, and the residence time of C that is sequestered initially in a system may be different from that of C sequestered later. Do the initial C and later C additions go through the same cycles? Lack of clear answers to several such questions is a formidable difficulty for realistically assessing the impact of agroforestry and other management practices on C sequestration.

Carbon Data Calculations: The most common inconsistency – though not unique to AFS – in reporting C stock and C sequestration data in AFS from different locations is related to soil. Soil C stock is conventionally expressed in mass per area such as t (=Mg) C ha^{-1}. These data are derived by multiplying the analytical data, which is usually in mass per unit mass of soil (g C 100 g $soil^{-1}$) with the soil's bulk density (BD) expressed in mass per volume of soil (g cm^{-3} or t m^{-3}), and with soil (sampling) depth. There is an anomaly in this conversion because the BD value involves a volume measure, whereas the C stock value is expressed in an area measure (ha). This problem is overcome by the assumption that C stock reported in t ha^{-1} is for 1 cm thickness (depth) of the soil unless the depth is specified. Thus, when the C stock to, say 40 cm or 100 cm depth is reported, that depth should be mentioned. Unfortunately, many reports on soil C stock in AFS either do not report such details or do not follow any uniform norm about the depth to which the data refer, leading to confusion and speculation when the data are compiled or compared. Nair et al. (2010) argued, based on accrued results from AFS research, that C stock in AFS should be reported to at least 1 m depth.

The importance of soil BD in these computations cannot be overemphasized but BD data are often not reported in many research papers on soil C sequestration in AFS. Consider two soils, soil A and soil B, both with the same C concentration of 2 g C 100 g $soil^{-1}$, but with different BD values, 1.0 and 1.2 t m^{-3}, respectively. The total soil C stock to 1 m depth in the two soils will be as follows:

Soil A: 2.0 g 100 g^{-1} x 1.0 t m^{-3} x 1 m = 200 t ha^{-1}
Soil B: 2.0 g 100 g^{-1} x 1.2 t m^{-3} x 1 m = 240 t ha^{-1}

[Note that the units of ha (= 10,000 m^2) and 1 m depth are accounted for in the calculation.]

Thus, soil B will have 20% more C stock than soil A to the same depth although both soils have the same C concentration (It is a different matter if both soils have the same C concentrations throughout the 1-m depth). The point is that while estimating C stock to 1 m depth factoring in BD values, soil B consisted of 20% more soil mass than soil A. Such differences are often overlooked while compiling regional and global datasets based on "standard" values of soil C stock (t C ha^{-1}). Therefore, the influence of soil bulk density on measured C stocks is particularly important when comparing land-use treatments that result in different BD values, as may be the case with AFS compared with annual crops or pastures. The problem is more serious when soil depth, to which the value reported is related, is not specified. A ramification of these issues is evident from a recent study by Hairiah (2020) reported from Indonesia. In that study, bulk density in the top 30 cm soil under non-tree agriculture increased by up to 30% relative to natural forest, leading to underestimation of soil carbon loss based on internationally agreed C-stock accounting. A global meta-analysis (see Section 20.5.2 for an explanation of meta-analysis) of 385 studies concluded that without soil mass correction, the effects of land-use change on soil carbon stocks in the tropics would be underestimated by 28% (Don et al. 2011). Thus, reporting soil BD data and soil depth is important, and exercising caution while using reported values of soil C sequestration is equally important.

Another issue is the "one-size-fits-all" approach to computations of regional and global statistics. Currently, most policy documents and projections, including major ones such as the IPCC reports, tend to assign a single, uniform value or sets of narrow-range values, for C stock and C sequestration potential of AFS irrespective of their site conditions and system characteristics. For example, the IPCC estimated that 630 million hectares of unproductive croplands and grasslands could be converted globally to agroforestry that could potentially sequester 1.43 and 2.15 Tg (Tg = 10^{12} g = megatons) of CO_2 annually by 2010 and 2040, respectively (IPCC, 2000). As stated above, the variability among soils to store C should be factored into such global estimates and projections.

In summary, methodological problems that are common to most land-use systems are of a higher order of magnitude in AFS because of the integrated, multispecies nature of the systems and the relatively slow growth rate of research on the subject. The methods, procedures, and estimations made in agroforestry research vary widely; therefore, the available datasets are mostly inconsistent and often inconclusive, especially in C sequestration studies. Several methodological challenges arising from difficulties related to sampling, analysis, computations, and interpretation make its measurement problematic. There is no easy and fast solution to these issues. At the very minimum, the researchers should accurately describe how the data being reported were collected, analyzed, and managed so that readers at large can understand and decide whether, how, and to what extent to incorporate the reported results in larger databases.

20.5 Reported Data on Carbon Sequestration Under Agroforestry Systems

When biological carbon sequestration was recognized as an important strategy in the global effort to address climate change in the 1990s, the strategy of "Land Use, Land Use Change, and Forestry (LULUCF)" of the Kyoto Protocol allowed the use of C sequestration through afforestation and reforestation including AF as a form of GHG offset activities under Article 3.3 of Kyoto Protocol, 1997 (https://unfccc.int/resource/docs/convkp/kpeng.html). Subsequently, numerous reports and other publications have reported the results of efforts to measure and estimate the potential of AFS to store and sequester carbon in the biomass and soils. A large body of scientific literature has accumulated on C sequestration under AFS. Nair et al. (2010) referenced most of such publications on AFS. Several others have appeared since; e.g., Abou Rajab et al. (2016); Cardinael et al. (2017); Jose and Bardhan (2012); Lorenz and Lal (2014); Post and Kwon (2000); Upson et al. (2016); Kim et al. (2016); De Stefano and Jacobson (2017); Chatterjee et al. (2018, 2019, 2020), and many others.

In all these studies, aboveground C sequestration estimates are direct manifestations of AGB production. The underlying processes of AGB production entail the uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation, and sequestration involves the additional step of "secure storage" of such fixed C (Section 20.3.2).

20.5.1 Soil Carbon Sequestration: Results from a Set of Multi-locational Studies

The C stock of soil depends on the inherent soil properties and processes and is influenced by management practices. Numerous studies on these issues related to agroforestry have been conducted around the world in the recent past. Salient aspects of a unique set of studies involving several agroforestry systems across different ecological regions around the world, and conducted according to a uniform research procedure by the University of Florida during two decades (2000 – 2019) are presented in this section.

1. ***Study locations and procedures.*** The study involved eight different locations on five continents. At each site, soil C storage was investigated concerning soil aggregate distribution under a locally popular agroforestry system in comparison with one or more other local land-use systems. The details of the study locations are presented in Table 20.5 and Figure 20.3. At all sites, soils were sampled up to at least 1 m depth in multiple depth classes and fractionated into three aggregate-size classes (250 – 2000, 53 – 250, and <53 μm), and the C content in each determined. Stable isotope ratio was used (Section 20.4.2) in some applicable situations to determine the relative contribution of trees and grasses to soil C. Results of the individual studies including the experimental details for each have been published in international peer-reviewed publications (see the footnote to Table 20.5). The distribution of the three aggregate-size fractions and the SOC content in each are presented in Table 20.6.
2. ***Significant findings.*** Soil organic carbon content in AFS in different locations in comparison with relevant other land-use systems in the same locations are presented in Figures 20.4, 20.5, 20.6, 20.7 and 20.8. A summary of the difference between AFS and comparable non-AFS expressed as percentages of C store

Table 20.5 Study location characteristics and brief descriptions of the agroforestry systems (AFS) and non-agroforestry systems (non-AFS) at the different sites

Site Description							
†Location; Coordinates	Climate (m.a.p, mm; mean temp. range, °C)	Soil order	Agroforestry systems (AFS)	Land uses: AFS and non-AFS	pH	Bulk density Mg m^{-3}	Age (i.e., since AFS establishment) yr "old"
1. Florida, USA. 28° to 29° N; 81° to 83° W	Humid subtropical 1330; −3 to 28	Spodosols	Silvopasture: slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*)	Pasture	5.5	1.5	50
				Silvopasture	5.4	1.5	12
		Ultisols		Pasture	6.2	1.7	55
				Silvopasture	5.7	1.6	14
2. Central Spain; 39° 59′ N; 6° 6′ W	Subhumid mediterranean 600; 8 to 26	Alfisols	Silvopasture: Dehesa (*Q. suber*)	Cork oak silvopasture	4.0	1.3	80
		Inceptisols	Silvopasture: birch (*Betula pubescens*) or pine (*Pinus radiata)* *plus Dactylis* spp./ *Trifolium* spp.	Birch silvopasture	4.2	1.4	80
				Pine silvopasture	4.1	1.4	80
				Pasture	4.2	1.5	Non-AFS
3. Kerala, India; 10°32' N; 76°14'E	Humid tropical 2700; 27 to 32	Inceptisols	Homegardens: Intensive multispecies mixtures of trees, shrubs, and herbs in small (< 0.5 ha) holdings; > 40-yr old	Forest	5.9	1.1	Non-AFS
				Homegardens	6.1	1.5	> 40
				Rice	6.0	1.3	Non-AFS
4. Ségou, Mali; 13° 20' N; 6° 10' W	Semiarid tropical 500 to 700; 29 to 36	Alfisols	Intercropping under scattered trees and plantings of live fences	Degraded land	5.2	1.3	Non-AFS
				Faidhelbia dominant	6.3	1.5	> 30
				Live fence	5.3	1.5	8
5. Bahia, Brazil; 14° 0' S; 39° 2' W	Humid tropical 1500; 25 to 32	Reddish-yellow Oxisols	Cacao (*Theobroma cacao*) under thinned natural forest (*cabruca*) or planted shade trees	Cacao Cabruca	4.8	1.1	30
				Cacao Erythriana	4.3	0.9	30
				Forest	4.2	0.8	Non-AFS
6. Minas Gerais, Brazil 17° 36' S; 46° 42' W	Cerrado: Subhumid tropical 1350; 20 to 30	Oxisols	Silvopasture: *Eucalyptus* spp. with understory of *Brachiaria* spp. (fodder grass)	Forest	5.1	1.0	Non-AFS
				Silvopasture	5.2	1.0	14
				Pasture	5.4	1.2	Non-AFS
7. Karnataka, India 12°54'–13°53'N; 75°04'–76°21'E	2400; Mean: 26	Ultisols & Alfisols	Coffee and tea under shade/ timber trees like *Erythrina* spp. *Gliricidia sepium* *Grevillea robusta* *Toona ciliata* *Acrocarpus* spp., *Albizia lebbeck, Melia dubia, Terminalia paniculata*	Coffee + Grevillea	6.3	0.96	~70
				Coffee + Mixed Shade	6.1	1.01	~55
				Tea + Grevillea	4.8	0.87	~85
				Homegarden	6.2	1.13	N/A
				Forest	6.3	0.67	Non-AFS

(continued)

Table 20.5 (continued)

Site Description			Agroforestry systems (AFS)	Land uses: AFS and non-AFS	pH	Bulk density Mg m^{-3}	Age (i.e., since AFS establishment) yr "old"
†Location; Coordinates	Climate (m.a.p, mm; mean temp. range, °C)	Soil order					
8. Turrialba, Costa Rica 9° 53' N; 83° 40' W	2600; Mean 22	Ultisols & Inceptisols	Conventional coffee + *Erythrina poeppigiana*	Int. Managed coffee + N-fixing trees	6.1	0.73	~15
			Conventional coffee + *Terminalia amazonia*	Int. Managed coffee + timber species	6.0	1.13	
			Organic coffee + *Erythrina poeppigiana*	Org Int. Managed coffee + N_2 species	6.3	0.86	
			Organic coffee + *Terminalia amazonia*	Org Int. Managed coffee + timber species	6.5	0.89	
			Coffea arabica	Full sun grown coffee	6.4	0.81	Monoculture
			Native, Talamancan montane forest	Forest	4.5	0.64	Non-AFS

†1. Haile et al. (2008, 2010); 2. Howlett et al. (2011a, b); 3. Saha et al. (2009, 2010); 4. Takimoto et al. (2008a, b); 5. Gama-Rodrigues et al. (2010); 6. Tonucci et al. (2011, 2017); 7. Chatterjee et al. (2019); 8. Chatterjee et al. (2020)

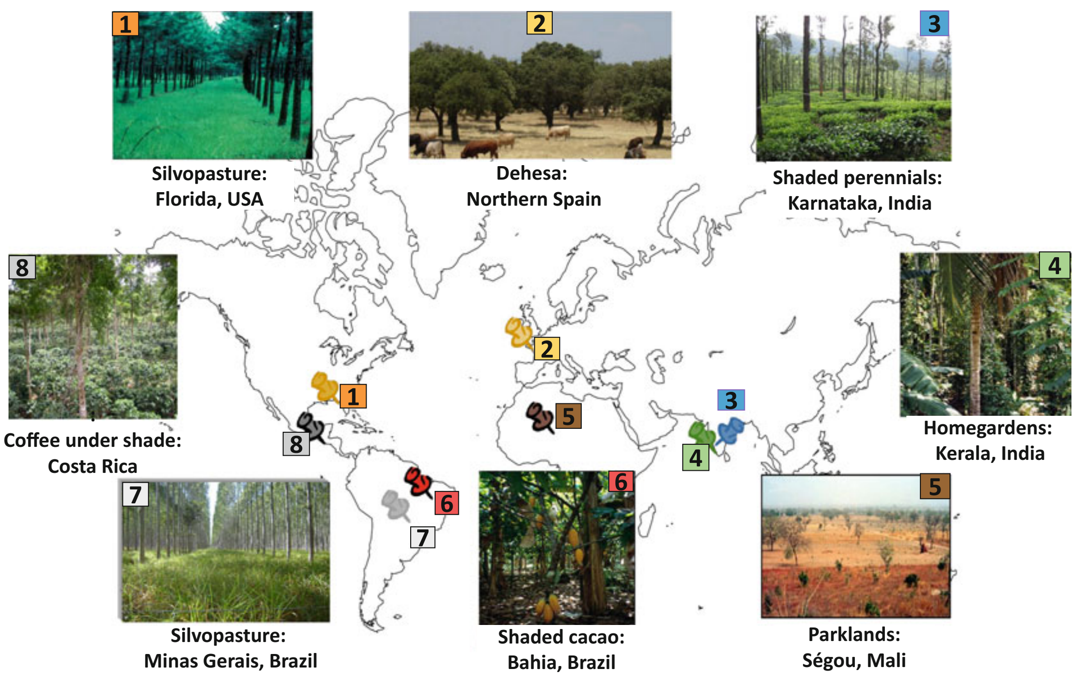


Figure 20.3 Multilocational research sites of studies on soil carbon sequestration under agroforestry systems conducted by the University of Florida, 2000–2019

Table 20.6 Percent weight of soil fractions, soil organic C (SOC) in the fractions, and particle sizes within 1 meter of a soil profile in land-uses in the USA, Spain, India, Mali, Brazil and Costa Rica

Land Use System	Soil order	SOC to 1m depth (Mg ha^{-1})	Size fractions (µm) (% of total soil by weight)			SOC (g kg^{-1} soil) in Soil size-fractions (µm)			Particle sizes g kg^{-1}		
			2000 – 250	250 – 53	< 53	2000 – 250	250 – 53	< 53	sand	silt	clay
Pasture, USA	Spodosols	182 to 266	33.23	62.55	2.14	4.19	5.98	0.04	960	20	20
Silvopasture, USA			33.65	60.92	2.39	5.82	7.31	0.06	960	20	20
Pasture, USA	Ultisols	76 to 108	44.12	48.69	3.23	2.56	1.40	0.04	905	30	65
Silvopasture, USA			44.32	49.48	2.74	2.75	1.26	0.03	930	30	40
Dehesa Oak, Spain	Alfisols	27 to 50	52.87	26.61	22.20	0.13	0.07	0.05	260	550	190
Birch silvopasture Spain	Inceptisols	80 to 177	51.43	37.00	9.71	0.77	0.97	0.39	665	153	185
Pine silvopasture Spain			50.60	38.75	9.69	0.66	0.96	0.25	665	153	185
Pasture (treeless) Spain			50.69	36.25	10.55	1.13	1.16	0.39	665	153	185
Homegardens, Kerala, India	Inceptisols	108 to 119	51.42	30.58	18.01	2.06	2.32	2.38	548	120	332
Forest, India			39.99	38.56	21.46	5.06	6.17	4.66	422	208	369
Rice paddy, India			50.72	33.46	15.83	0.92	0.66	1.06	786	99	115
Parklands, Mali	Alfisols	22 to 38	13.35	38.08	48.57	1.14	3.12	5.95	795	79	126
Live fence, Mali			21.44	26.36	52.20	0.61	2.72	2.50	793	86	121
Degraded land, Mali			17.06	39.56	43.37	2.93	5.65	7.04	600	152	156
Cacao cabruca, Bahia, Brazil	Oxisols	300 to 320	68.06	21.52	7.69	26.02	8.57	3.06	502	26	472
Cacao + erythrina, Bahia			74.50	18.09	5.95	34.21	8.04	2.97	396	34	570
Forest, Bahia			72.12	19.05	5.92	32.89	8.55	2.86	377	24	599
Eucalyptus silvopasture, MG, Brazil	Oxisols	385 to 460	54.65	26.97	14.13	26.54	11.94	6.93	145	109	747
Pasture, MG			45.88	26.10	23.71	19.42	10.41	9.96	151	240	606
Forest, MG			57.47	22.54	16.40	27.99	9.75	8.38	166	242	592
Coffee + Grevalia, Karnataka, Ind	Ultisols & Alfisols	142	48.92	33.42	25.34	7.67	3.32	3.25	424	180	396
Coffee + Mixed shade, India		105	45.26	37.23	21.69	5.76	2.50	2.22	380	224	396
Tea + Grevillea, India		116	57.28	27.97	17.88	7.16	2.37	2.03	252	268	480

(continued)

Table 20.6 (continued)

Land Use System	Soil order	SOC to 1m depth (Mg ha^{-1})	Size fractions (μm) (% of total soil by weight)			SOC (g kg^{-1} soil) in Soil size-fractions (μm)			Particle sizes g kg^{-1}		
			2000 – 250	250 – 53	< 53	2000 – 250	250 – 53	< 53	sand	silt	clay
Homegarden, India		89	47.57	38.63	17.19	4.55	2.49	1.89	428	292	280
Forests, India		172	67.38	23.26	10.95	119.1	2.93	2.37	432	188	380
Conventional Erythrina, Costa Rica	Inceptisols & Ultisols	102	72.95	20.83	16.80	7.07	1.75	1.67	376	408	216
Conventional Terminalia, Costa Rica		109	66.45	25.35	19.65	7.21	2.10	1.59	368	420	212
Forests, Costa Rica		147	81.08	18.88	17.55	10.8	2.54	1.27	292	584	124
Organic Erythrina, Costa Rica		114	68.40	22.63	14.8	7.69	2.54	1.17	376	404	220
Organic Terminalia, Costa Rica		126	67.85	25.00	16.25	8.50	2.37	1.67	476	304	220
Sun coffee, Costa Rica		92	61.45	27.35	17.35	6.54	1.62	1.07	332	424	244

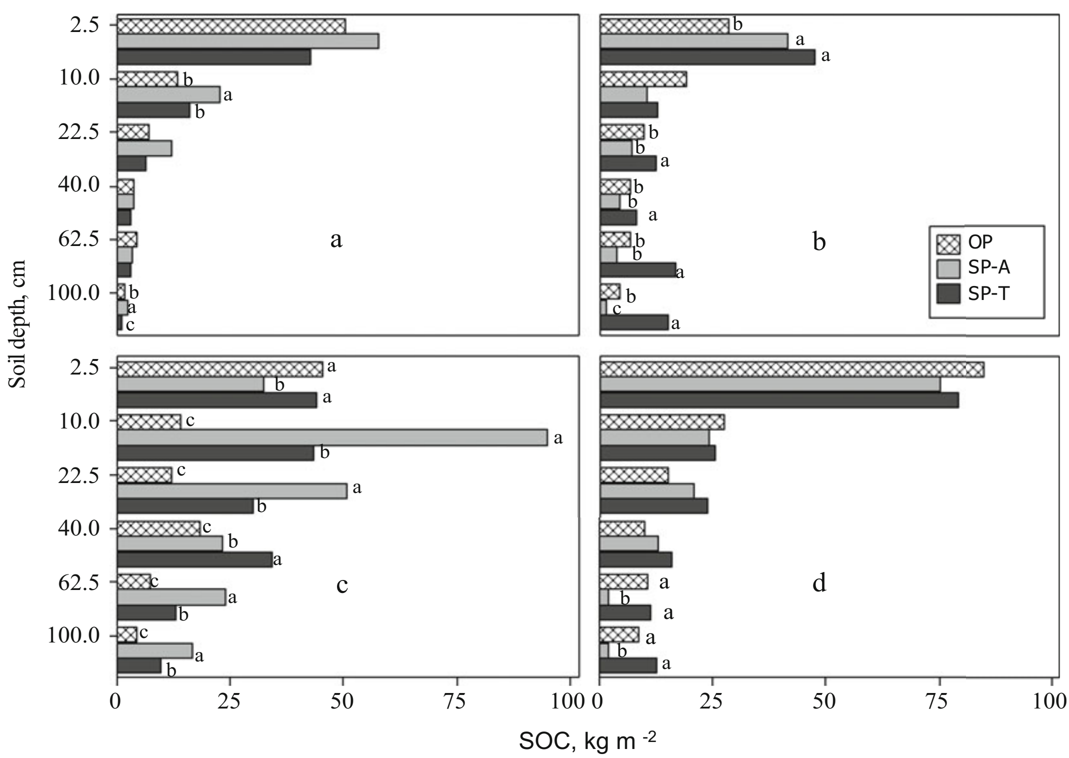


Figure 20.4 Soil organic carbon (SOC) with depth at three pasture locations (silvopasture: center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for whole-soil of the Alachua (**a**), Suwannee (**b**), Hardee (**c**) and Osceola (**d**) sites in Florida, USA. Lower case letters indicate significant differences in SOC among pasture locations at a given depth and site. Depth indicated is the mid-point of the sampled depth. (Source: Haile et al. 2008; reproduced with permission from *Journal of Environmental Quality*)

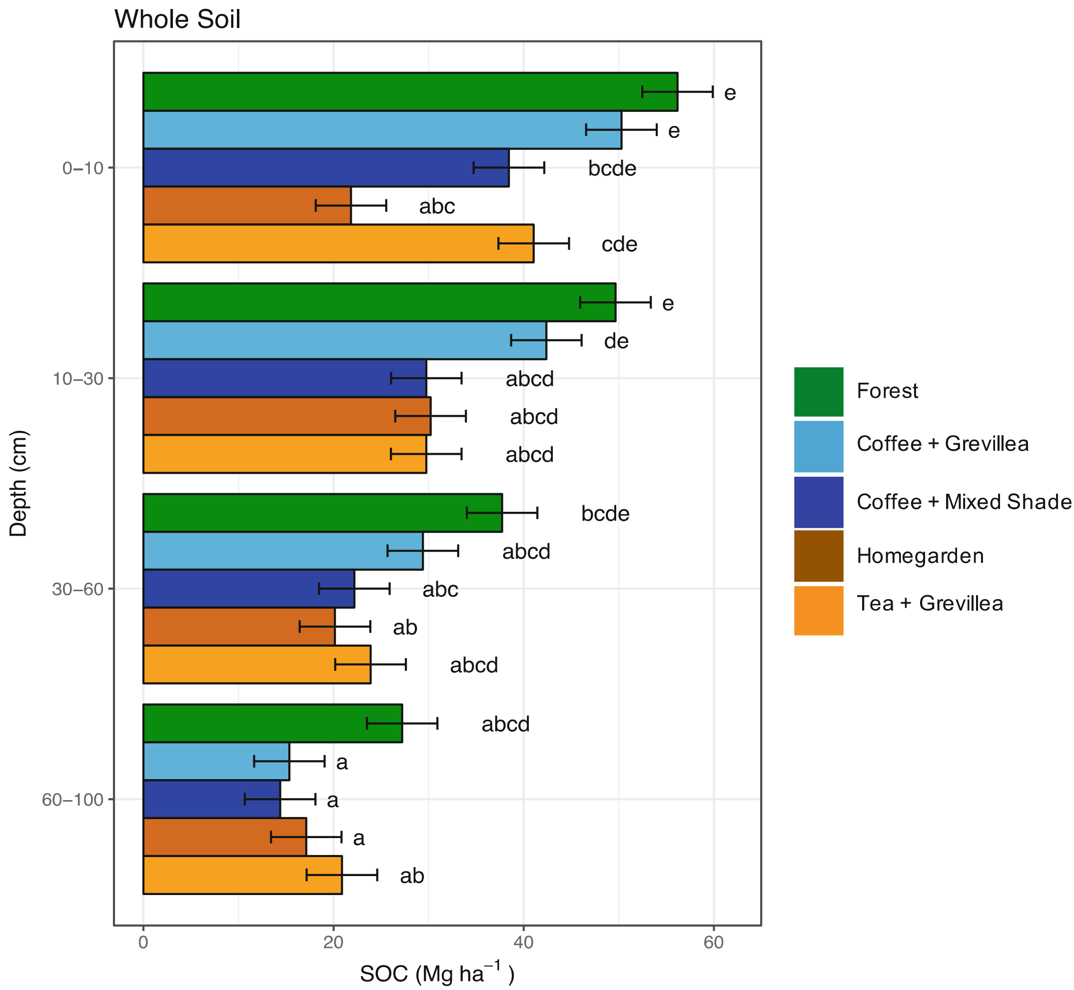


Figure 20.5 Depth-wise mean soil organic carbon (SOC) in Mg C ha^{-1} stock in the whole soil up to 1 m depth in five different land-use systems in Koppa, Karnataka, India. (*Note: Tukey's test was used to determine significant differences among mean SOC within land-use systems. Lower case letters indicate differences (at the 0.05 probability level) in SOC among land-use systems for soil depth within 1 m. The error bars indicate standard error of the mean*). (Source: Chatterjee et al. 2018, reproduced with permission from *Agroforestry Systems*)

in the AF system at different locations is given in Figure 20.9. The salient results of this multi-locational study include:

- The amount of C stored in soils depends on the soil's properties and characteristics, especially silt + clay content (Haile et al. 2010; Takimoto et al. 2009).
- Tree-based agricultural systems, compared to treeless systems, generally store more C in deeper soil layers under comparable conditions (Figure 20.4).
- Long-term AFS (e.g., shaded perennials) store similar or more amounts of SOC in upper soil layers compared with adjacent natural forests (Figure 20.5).

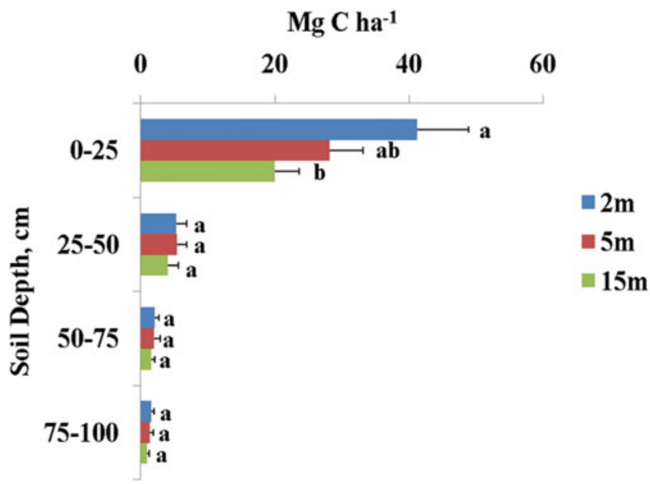


Figure 20.6 Soil carbon storage in the whole soil in different soil depths up to 100 cm as it varies from distance to *Quercus suber* L. in the whole soil at the St Esteban Farm, Extremadura, Spain. At each depth, means that differ statistically (at $p < 0.05$) are labeled with different lower case letters. (Adapted from Howlett et al. 2011a, b. Source: Redrawn from a complicated figure in *Journal of Environmental Monitoring*)

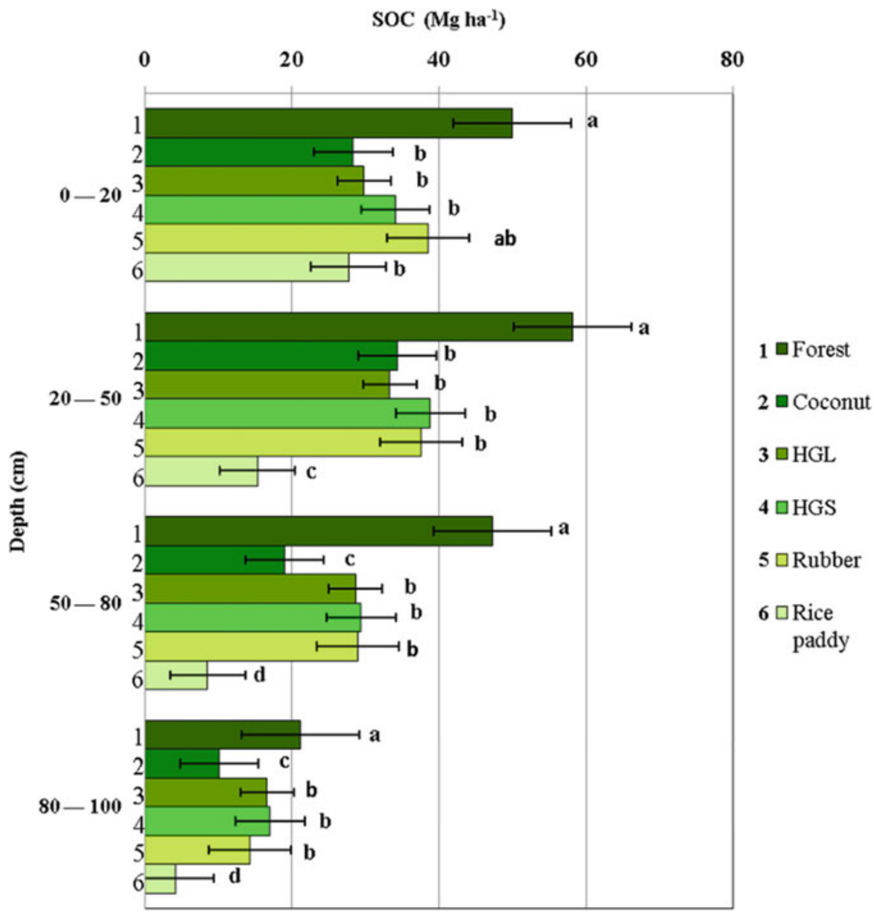


Figure 20.7 Mean soil organic carbon (SOC) content in the whole soil of six different land-use systems across soil depth classes in Thrissur district, Kerala, India. Lower case letters indicate differences (at the 0.05 probability level) in SOC among land-use systems compared within each depth class. Numbers 1 to 6 on the left (y-axis) of various depth classes refer to the different land-use systems. HGL = Large Homegarden (> 0.4 ha); HGS = Small Homegarden (< 0.4 ha). (Source: Saha et al. 2010; reproduced with permission from *Plant and Soil*)

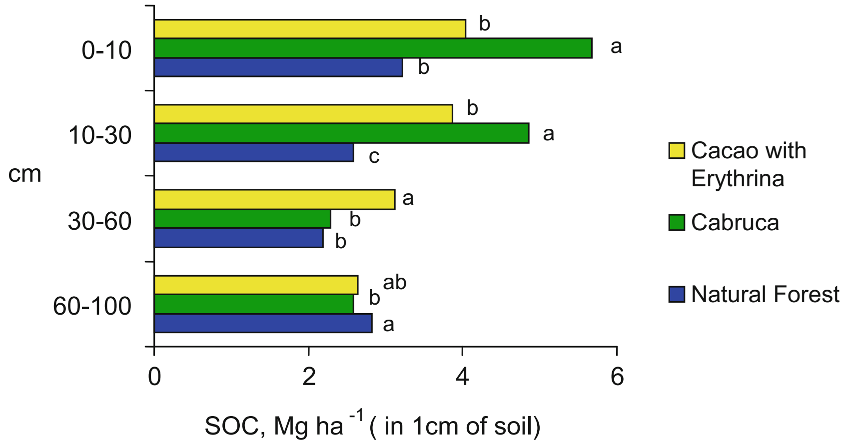


Figure 20.8 Soil organic carbon (SOC) storage at different depths in three land-use systems in Bahia, Brazil. Values followed by the same letter (s) within each depth are not significantly different according to the Tukey test ($P = 0.05$). (Source: Gama-Rodrigues et al. 2010; reproduced with permission from *Environmental Management*)

- Higher SOC content is associated with higher species richness and tree density (Saha et al. 2009).
- Soil near the tree, compared to away from the tree, stores more C (Howlett et al. 2011a, b: Figure 20.6; Takimoto et al. 2009); C3 plants (trees) contribute to more C in the silt + clay-sized (<53 μm) fractions than C4 plants in deeper soil profiles (Haile et al. 2010).

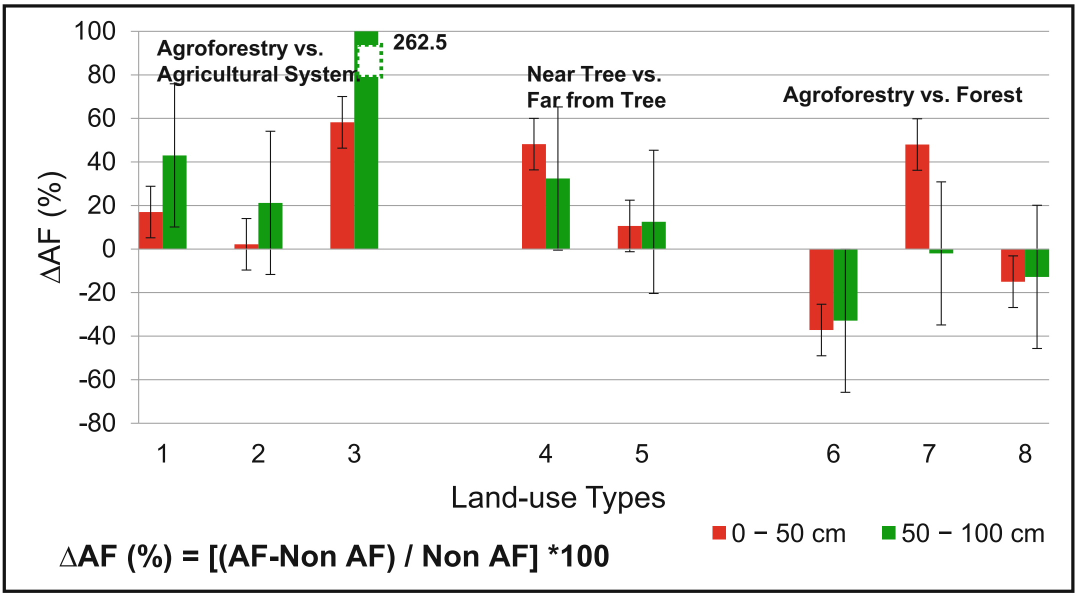
Another study of this nature that has just been published (Pinheiro et al. 2021) included silvopastoral systems of Eucalyptus hybrids planted at different plant densities and configurations with forage species of the genera *Urochloa* (syn. *Brachiaria*) and *Panicum* as the understory in the Cerrado region (Oxisols) of Minas Gerais state, Brazil. The results corroborate the above overall findings, but the study details and results are not included in Section 20.5.1 (Tables 20.5 and 20.6; Figure 20.3).

In summary, these results indicate that agroforestry systems store higher amounts of carbon, compared to single species cropping and grazing systems, in both aboveground and belowground compartments of the system. The carbon sequestration potential of AFS seems especially significant in the soil, particularly in soil depths below 50 cm. The extent of C sequestration will depend on several site-specific factors as well as system management.

20.5.2 Meta-analyses

A meta-analysis is a statistical procedure for comparing and synthesizing results from different studies for finding common patterns, discrepancies, or other interesting relationships that may not be detectable from individual studies (Borenstein et al. 2009). When the treatment (or effect size) is consistent among studies, meta-analysis can be used to identify this common effect.

The procedure is now commonly used in agricultural and natural resources research as a comprehensive approach to discern the common trends and directions from multiple studies. It seems particularly useful for analyzing the datasets on carbon sequestration under AFS that are increasingly becoming available at varying levels of details from numerous studies using different methods. While the available information on C stocks reported in Section 20.5.1 is extremely useful for understanding the existing situations, they



#	Systems; age (# years since AF system installation)	Location	Soil Order
1	Pine + pasture vs. treeless pasture; 30 yr	Florida, USA	Ultisols
2	Pasture under birch trees vs. treeless pasture;	Northern Spain	Inceptisols
3	Home garden vs. rice paddy; >50 y	Kerala, India	Inceptisols
4	Under tree vs. away from trees (Dehesa); 80 y	Northern Spain	Alfisols
5	Under trees vs. away from trees; Parkland system; >50 y	Ségou, Mali	Alfisols
6	Homegarden vs. forest: >50 y	Kerala, India	Inceptisols
7	Cacao under shade vs. forest; > 30 y	Bahia, Brazil	Oxisols
8	Brachiaria + Eucalyptus vs. Treeless forage stand; 30 y	Minas Gerais, Brazil	Oxisols

Figure 20.9 Differences in soil carbon stock to 1 m depth between comparable agroforestry (AF) and agricultural systems, near the trees and away from trees in AFS, and AF and natural forests, expressed as percent of non-AF system values, at different locations. See Table 20.5 for additional site- and system details. (Source: Nair et al. 2010; modified with permission from *Advances in Agronomy*)

represent only one point (snapshot) in the continuum of land-use changes. They are inadequate to predict the rate of change in SOC with alterations in land management practices from agriculture to AFS (introducing trees into agricultural fields) or forest to AFS (converting forestlands into AFS by outright forest clearing and AFS establishment or thinning existing forest and underplanting shade-tolerant specialty species). Such information is needed for assessing the benefits of agroforestry adoption in terms of economic advantages and incentives for local farmers.

Some efforts of meta-analyses for understanding the effects of adopting specific land management practices on SOC stocks and other ecosystem services have been reported for several land-use systems. Berthrong et al. (2012) evaluated how afforestation affected SOC and some soil properties (N, pH, and CEC) across pine plantations. Guo and Gifford (2002) found SOC stocks declined after conversion from pasture to a plantation, native forest to crops, and pasture to crops. Reporting the results from a meta-analysis on the effect of cover crops on C sequestration in agricultural soils, Poeplau and Don (2015) suggested that cover crops significantly improved SOC stock to an average of 16.7 t C ha^{-1} than the reference croplands. A global meta-analysis by Don et al. (2011) found that if agricultural land was afforested, SOC improved by 29%, and when cropland was converted to grassland, the increase was 26%.

Two meta-analyses that are specific to AFS were reported recently (Kim et al. 2016; De Stefano and Jacobson 2017). Chatterjee et al. (2018) reported a study focused on understanding the trend of SOC stock changes (ΔSOC) across Forest-Agroforest-Agriculture/Pasture continuum in different agroecological regions where agroforestry is practiced. It included data from 78 peer-reviewed studies giving 858 data points across four agroecological regions and six categories of agroforestry systems. The major findings of the study (Figure 20.10) were:

- Overall, AFS increased the SOC stocks up to 100-cm soil depth in the tropics, but not always in the temperate regions (attributable to the so-called C Saturation in Temperate soils, Stewart et al. 2007; Table 20.7).
- The extent of AFS-induced SOC storage varied significantly across a range of agroecological regions, age of the system, soil depth, and ecological (climatic and soil) conditions.
- The potential role of AFS in food security and climate change mitigation through SOC improvement could be more relevant in the tropical regions where the soils are known to be C-depleted than in the C-saturated temperate soils.

A meta-analysis by Feliciano et al. (2018) using data from 86 publications found that soil carbon sequestration among agroforestry systems was highest in silvopastoral systems (4.38 t C ha^{-1}), and aboveground carbon sequestration was highest in improved fallows (11.29 t C ha^{-1} yr^{-1}). On average, carbon benefits of AFS were greater in tropical climates than in other climates in terms of both soil C (2.23 t C ha^{-1} yr^{-1}) and aboveground C (4.85 t C ha^{-1} yr^{-1}). Furthermore, the highest aboveground C sequestration (12.8 t C ha^{-1} yr^{-1}) occurred when degraded land was replaced by improved fallow, whereas the conversion of a grassland system to a silvopastoral system resulted in higher soil C sequestration (4.38 t C ha^{-1} yr^{-1}). The authors also found that the lack of data on C stocks before implementing the land-use change and the lack of details on soil sampling design and variances were the main limitations in the data.

These results show that the meta-analyses can provide a general trend of changes in C sequestration rates under AFS in comparison to agricultural and forestry systems. Such information is valuable for planning the nature of research and development efforts on a broad scale for a region or country when such information is needed for assessing the benefits associated with AFS adoption in terms of economic advantages and incentives for local farmers.

20.5.3 Carbon Saturation in Soils

Generally, estimates of soil C storage potential are based on models or factors that assume linearity between C input levels and C stocks at a steady-state, implying that SOC stocks could increase without limit as C input levels increase (Stewart et al. 2007). Some soils, however, show little or no increase in steady-state SOC stock with increasing C input levels suggesting that SOC can become saturated for C input. Carbon saturation refers to such a limit to the SOC accumulation. Its significance is that when C saturation is close to 100%, additional SOC may not result in any additional sequestration. The limit is believed to be determined by the silt and clay content of a soil horizon, especially in smaller-sized aggregates (microaggregates, 250 – 53μm; and silt+clay fraction, < 53μm). Saturation is highest (close to 100%) in undisturbed natural systems and lowest in C-depleted soils of the tropical (smallholder) farming systems. Based on an analysis of long-term field experiment data, Stewart et al. (2007) concluded that the greatest efficiency in soil C sequestration will be in soils farther from C saturation. Thus, C sequestration potential through agroforestry could be expected to be high in C-depleted soils of the tropical (smallholder) farming systems.

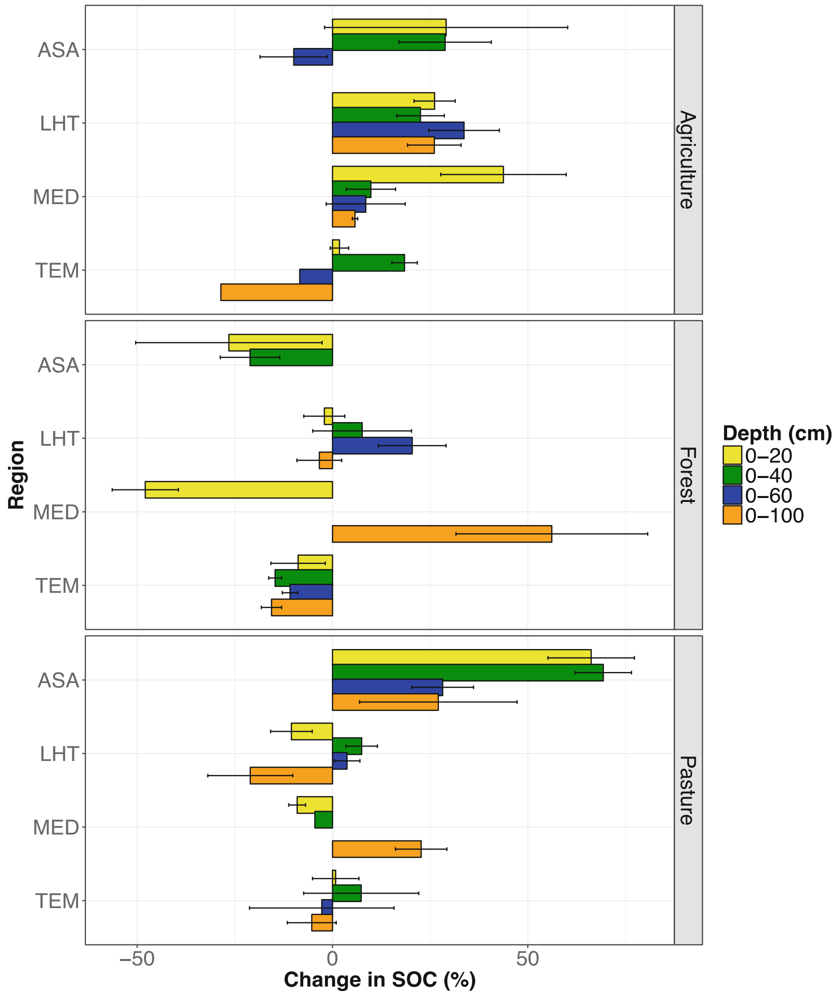


Figure 20.10 Summary of results of a global meta-analysis showing percentage differences in soil organic carbon stock (Change in SOC, %) between Agroforestry systems (AFS) vs. Agriculture/Forestry/Pasture in four soil depth classes (0–20, 0– 40, 0–60, and 0–100 cm) in three major agroecological (arid and semiarid (ASA), lowland humid tropics (LHT), and temperate (TEM) regions around the world. Positive values represent increase in SOC % under AFS, and negative values represent reduction in SOC under AFS, compared to the system concerned. The analysis was based on 858 data points derived from 78 publications in international peer-reviewed journals. (Source: Chatterjee et al. 2018; reproduced with permission from *Agriculture, Ecosystems and Environment*)

Table 20.7 Overall differences in soil organic matter status between agroforestry systems versus agriculture/forestry systems under comparable conditions in the tropics and temperate regions, based on a global meta-analysis

Comparison	ΔSOC%	95% Lower CI ¶	95% Upper CI ¶
AFS vs. Agriculture (Tropical)	23.63	15.70	31.56
Forest vs. AFS (Tropical)	−8.96	−16.12	−1.80
AFS vs. Agriculture(Temperate)	2.80	−3.18	8.79
Forest vs. AFS (Temperate)	−13.06	−21.76	−4.35
AFS vs. Agriculture (overall)	16.38	10.65	22.10
Forest vs. AFS (overall)	−9.74	−15.68	−3.80

ΔSOC % = percentage change in SOC; CI¶ = Confidence Interval
Lower and Upper CI represent the lower and upper limits for the mean (ΔSOC%) values at 95%
Source: Chatterjee et al. (2018)

20.5.4 Carbon Sequestration Potential of Agroforestry Systems: Summary

While the potential of agroforestry adoption as a climate mitigation strategy is getting well recognized, the extent of carbon sequestration benefit that can realistically be attained under various conditions is still not well established. Numerous datasets are available as reported in the previous sections. However, the influence of different site-specific soil- and climatic factors, management practices, and socioeconomic characteristics have a significant impact on the extent of C sequestration. Moreover, the lack of standardized procedures for the determination of C sequestration under various field conditions makes many estimations less rigorous and even questionable. Several estimates of the amounts of C sequestration under different systems and locations have already been referenced in this chapter (Sections 20.5.1 and 20.5.2; Table 20.2). Some such estimates, even if not rigorous, attain "pseudo-authenticity" through repeated citations. With these caveats, Nair et al. (2009b) prepared some "best-bet estimates" of the ranges of SCS (soil C sequestration) under different AFS in the major agroecological regions of the tropics. The suggested values ranged from 5–10 kg C ha^{-1} in about 25 years in extensive tree-intercropping systems of arid and semiarid lands to 100–250 kg C ha^{-1} in about ten years in species-intensive multistrata shaded perennial systems and homegardens of humid tropics (Table 20.8). Qualifiers such as low, medium, and high are also often used in C sequestration literature in AFS without explaining what those qualifiers indicate. Toensmeier (2016) defined the aboveground C storage, presumably biomass, as (all numbers in t C ha^{-1} yr^{-1}) very low (< 0.5), low (0.5–1.0), medium (1–5), high (5–10), very high (10–20) and exceptionally high (> 20.0). It may, however, be noted that biomass is not the same as sequestered C (Section 20.4.3). Toensmeier (2016) also ranked soil C stock (t ha^{-1}) as modest (< 50), large (50–150), and very large (> 150), soil depth not indicated. These qualifiers are within the limits of the generally reported values of aboveground and soil C stocks in agroforestry systems and can be considered acceptable for practical purposes until they get replaced by more rigorous standards.

20.6 Agroforestry Management for Carbon Storage and Climate-Change Mitigation

As described in Section 20.5, agroforestry was recognized as one of the best management practices of the afforestation and reforestation activities under the Kyoto Protocol, 1997, for restoring at least some of the carbon that is lost over the decades or centuries due to land cultivation. The predictions on the effects of such practices are based primarily on their expected effects on biomass productivity of the components. The soil and plant (tree) management practices that have a bearing on the net effect on C sequestration and climate-change mitigation are too many to be discussed here; therefore, the discussion here is limited to a couple of topics that have attained prominence lately.

20.6.1 Biochar Use in Agroforestry

One of the recent developments in the use of biomass for soil carbon management is the increasing interest in biochar. The term that started appearing in the literature in the early 2000s has become hugely popular since. The International Biochar Initiative (IBI: http://www.biochar-international.org/) describes biochar as *"a solid material obtained from the carbonisation of biomass.* Simply stated, biochar is *a carbon-rich organic material produced by pyrolysis of biomass* such as wood, manure, or crop residues and byproducts (Lehmann and Joseph 2009). Pyrolysis is the process of *combustion* at low or no oxygen. It is different from combustion in the presence of oxygen as in the case of traditional charcoal making, such that the emission of CO_2 and methane that occurs during

Table 20.8 Indicative values of soil carbon stock and sequestration potential under major agroforestry systems in the tropics[a]

Major ecological regions and agroforestry systems	System characteristics: E = existing N = new plantings TD = tree density (# ha^{-1}) Age in years (yr)	Soil carbon (Mg C ha^{-1})[b]		Timeframe for realizing the potential (yr)[c]
		Stock to 50 cm soil depth	Potential for additional C sequestration to 100 cm depth	
Humid Lowlands				
Shaded perennial systems	E > 15 yr	100–200	20–30	10
	N or < 5-yr-old	70–150	100–200	
Alley cropping	E > 5 yr-old	20–45	25–75	>5
	N or < 5 yr	20–70	30–120	>10
Homegardens	Low TD < 75	60–90	70–150	>20
	Medium TD > 75	70–120	100–180	>20
Tree intercropping	E, Low TD < 50	20–80	50–100	>20
	E, Med TD 50–100	40–100	70–120	
	E, High TD >100	50–120	80–150	
Silvopasture (Grazing systems)	E, Low TD < 25	80–100	80–120	>20
	E, High TD > 25	80–120	90–150	
Silvopasture (Fodder bank)	E > 10-yr-old	60–95	30–60	
	N or young < 8 yr	75–95	50–150	
Woodlots	E > 10 yr	80–100	40–60	>20
	N or young < 8 yr	50–80	50–150	
Tropical Highlands				
Shaded perennial systems	E > 15 yr	100–200	20–50	10
	N or young, < 5-yr-old	70–150	100–250	
Alley cropping	E > 5 yr	30–60	40–70	>5
	N or young, < 5 yr	20–70	40–120	>10
Homegardens	E > 5 yr	50–80	70–150	>20
	N or young < 5 yr	70–150	100–200	
Silvopasture (Grazing systems)	E, Low TD < 20	70–120	80–150	>20
	E, High TD > 20	80–150	90–160	
Silvopasture (Fodder bank)	E > 10 yr	60–100	30–70	>20
	N or young < 5 yr	75–110	60–150	
Woodlots	E > 10-yr-old	80–100	40–70	>20
	N or young < 5 yr	50–80	60–170	
Arid and Semiarid Lands (mostly lowlands)				
Intercropping systems, Parklands	E ~ 50 trees	30–40	5–10	> 25
	Enrichment planting	20–30	30–50	> 25
Silvopasture (semiarid)	E ~ 50 trees	30–40	5–10	> 15
Grazing systems	N	20–30	30–50	> 10
Fodder bank	N		30–100	
Fuelwood lot	N			

[a]"Best-guess" estimates based on literature data (from nearly 150 peer-reviewed papers)
[b]Reported values, and therefore the estimates, are mostly are for the 0–50 cm depth
[b, c]The values in column 4 (additional C seq potential) are for up to 1 m depth considering the substantial amounts of tree roots and the SOC in deeper soil layers. It is assumed that (1) the existing systems have only limited potential in SCS unless they are significantly modified by management interventions such as new (tree) planting and fertilization, and (2) fairly long periods of time (column 5) are required to realize the potential for additional C sequestration in soils

Figure 20.11 Typical profiles of "Terra Preta" (**a**) and Oxisol (**b**) sites. (Source: Glaser et al. 2001; reproduced with permission from *Naturwissenschaften*)

the natural decomposition of biomass or charcoal-making by burning the wood could be considerably reduced. The most-referenced example of the effect of biochar on soil productivity is the biochar-rich dark- earth (*Terra Preta)* that appears in patches in a small region (approximately 20 ha) of the highly weathered, infertile Oxisols in Central Amazonia, Brazil. These patches, although under continuous cultivation for centuries, have maintained high productivity levels compared to the surrounding soils of the region; see Figure 20.11 for a visual comparison of the profiles of a *Terra Preta* soil and the dominant soil type of the region. The *Terra Preta* soils are formed from the *slash and char* technique – as opposed to the traditional *slash and burn* (see Chapter 5, Section 5.2): the previous inhabitants of the land are believed to have added to the soil large quantities of nutrient-rich residues of fruits, bones, ashes, excreta, etc. over long periods (Glaser 2007).

Feedstock: The biomass resources used for biochar production are called **feedstock** – *not to be* confused with feedstock used in animal production including silvopastoral systems. When the feedstock is pyrolyzed on a commercial scale, the pyrolysis gases flow into a thermal oxidizer, which combusts the gases and oils at high temperatures achieving clean combustion. At smaller scales, biochar is often prepared in small, cost-effective kilns. The quality and properties of biochar depend on the nature of the feedstock and the method of pyrolysis.

Biochar as a Source of Plant Nutrients: Biochar is now being recommended as a nutrient source especially in nutrient-deficient and degraded soils (Novak et al. 2009; Ippolito et al. 2012; Nair et al. 2017). Numerous reports and meta-analyses results are available on the effect of biochar application on crop growth (Biederman and Harpole 2013), nutrient dynamics (Glaser and Lehr 2019; Gao et al. 2019), soil amelioration, microbial biomass, and soil respiration (Zhou et al. 2017), and soil physical properties (Blanco-Canqui 2017). Briefly, biochar from the same source added at a given rate to different soils could have different effects – particularly for phosphorus – based on the respective soil properties (Nair 2014). The elemental composition of a feedstock is not an indication of plant-nutrient availability in the biochar made from that feedstock (Freitas et al. 2020); and, the risk of nutrient loss during biochar application depends on the nutrient release potential of the biochar as well as the nutrient retention properties of the soil (Dari et al. 2016).

Biochar and Soil Carbon Sequestration: Any biomass added to the soil is subjected to decomposition and most of the C in the added material is reverted to the atmosphere as discussed in Chapter 16, Section 16.3. But the conversion of agriculture and forestry biomass (feedstocks) into biochar could reduce CO_2 and methane emissions during the natural decomposition or burning of the material. Seventy to 80 percent of biochar is C and about 60% of this biochar C is highly stable (Cooperman 2016). Wang et al. (2016) reported based on a meta-analysis of biochar decomposition in soil and estimation of its mean residence time (MRT) using 128 observations of biochar-derived CO_2 that only 3% of the biochar was bioavailable, the remainder contributing to long-term C storage in the soil. Based on an evaluation of 76 biochars from 40 studies, Brassard et al. (2016) reported that biochars with lower N content (C/N ratio >30) were more suitable for mitigation of N_2O emissions from soil, and those produced at higher pyrolysis temperature could have high C sequestration potential. Hardwood biochars with a higher C/N ratio will, therefore, be more suitable for the mitigation of soil N_2O compared to biochars from animal-based sources (Table 20.9). One of the important attributes of biochar that makes it especially important for climate-change mitigation is that the C in biochar resists decomposition: "biochar can hold carbon in soils for hundreds to thousands of years" as evidenced by the *Terra Preta* soils (Lehmann et al. 2006). Lately, biochar application to agricultural soils has received considerable research attention, as it is considered a soil-based greenhouse mitigation strategy for sustainable environmental management (Paustian et al. 2016). Moreover, based on the emission-reduction potential due to the avoidance of fossil fuel fertilizers, the contribution of biochar application to GHG emission-reductions could be calculated as credits and sold on a GHG emission trading market as proposed by van der Gaast and Spijker (2013).

Table 20.9 Nutrient composition of biochar produced from plant- and animal-based feedstocks

	P	K	Ca	Mg	TKN	TP	TC	C/N	pH	EC
	mg kg^{-1}						%	ratio		ms cm^{-1}
	Plant-based biochar									
HWB	480	4350	670	620	1015	1900	77	755	8.8	180
Maple	103	4140	4810	670	3048	730	57	186	7.8	275
Pine	67	450	490	47	0.1	405	NA†	NA	8.4	59
	Animal-based biochar									
PLB[1]	13 100	48 300	10 300	6190	18 000	29 000	30	15	9.3	20
PLB[2]	16 900	57 000	13 700	8280	28 300	28 100	30	11	9.1	45
Biosolids	7060	500	2 330	5140	50 700	67 330	32	6	6.4	50

Notes:
HWB = Hardwood biochar; PLB[1] and PLB[2] = Poultry litter biochar from two different production batches
Mehlich 3 extractable: P (phosphorus), K (potassium), Ca (calcium), and magnesium (Mg);
TP = Total phosphorus; TKN = Total Kjeldahl nitrogen; TC = Total C; EC = Electrical conductivity
†NA = Not Available
Adapted from Freitas et al. (2020)

Biochar and Agroforestry Systems: In addition to the overall importance of biochar in soil and carbon management, an issue of special relevance to agroforestry is that several byproducts from AFS can be used as excellent biochar feedstocks. These include wastes from non-destructively harvested tree crops such as palms, coffee, cacao, and a variety of other species. Materials such as coconut husk and shells, the outer covering of cacao pods, stalks and straw of cereals, and a variety of other locally available materials are excellent feedstocks of biochar. Additionally, there are animal-based resources such as poultry litter and manure from cattle, pigs, chicken, and turkey.

Field investigations on the effects of biochar application to tree crops and agroforestry systems have, however, been relatively limited. Applying wood biochar at 0%, 5%, 10%, and 20% on a volume to volume basis to an avocado farm in Australia, Joseph et al. (2020) reported significant improvement in the growth of avocado seedlings and increased fruit yield in the first three years after planting (compared to the control). From a study on the effect of biochar application on soil carbon stock in a coffee agroforestry system in Nepal, Dahal et al. (2018) reported a significant increase in soil C stocks in the biochar applied plots at three locations of the study. In a two-year field study on the effects of poultry litter biochar (PLB) on a rotational (agronomic) cropping cycle in Entisols and Spodosols in Florida, USA, Freitas et al. (2018) reported higher corn yield from the biochar-applied treatments compared with the inorganically fertilized and the No-P added plots on the Entisols, but no difference on the Spodosols after a biochar application of 760 kg poultry litter biochar ha^{-1}. The relevance of this study to the AF context is the importance of understanding the compositional variations in biochars from different feedstocks for their judicious use as a fertilizer source.

Although many of the available reports have presented impressive results on the effect of biochar application on various crop-growth-promoting factors, the principles and the mechanisms underlying such results have not been adequately articulated. Moreover, most of the reported studies are laboratory- or green-house based; the limited number of field studies reported have been of a relatively short duration of two years or less, and all soil-process investigations have been confined to the top 30 cm (or lesser) soil depths. Further, as pointed out earlier, the reported results are highly variable depending on the soil types, feedstocks, and pyrolysis methods used for biochar preparation. The numerous meta-analyses studies do not address these inherent weaknesses of the data used for the analyses. So much so, a widely applicable set of recommendations on the use of biochar has not yet become available even for annual crops, let alone the perennial systems such as tree crops and agroforestry. Nevertheless, there are some opportunities for biochar application to specialized situations in AFS (Nair et al. 2017). For example, biochar application to AFS tree nurseries and spot application in the planting pits of trees (e.g., for the establishment of nitrogen-fixing trees in acid soils) are worth investigating. The high water-holding capacity of biochar is an attribute that could be exploited successfully for tree planting in arid and semiarid lands. Further, co-application of biochar with limited quantities of inorganic fertilizers in high-value and commercial AFS such as shaded perennial systems could reduce the overall cost of production and reduce the carbon footprint of fertilizer use. Biochar production from agroforestry "wastes" will also minimize costs associated with off-site disposal of such waste materials. Biochar application in agroforestry systems is an area that deserves further research and development attention.

20.6.2 Tree Selection and Management

Most discussions on C sequestration emphasize the importance of management practices on C sequestration, especially in soils, and most predictions on the effects of management practices on C sequestration are based on the expected effects of such practices in biomass productivity of the system's components. Other than that, the C sequestration potential of tropical tree taxa is highly variable (Nair et al. 2010), the information that is available on this topic is limited. It originates from reports on C sequestration in tree plantations where C sequestration is considered synonymous with C stock (Nair et al. 2009a, b), which is erroneous. Moreover, the effects of silvicultural practices such as stand-density management, weed control, and harvesting that influence the growth of a single-species plantation may not apply to C sequestration in AFS involving that species where it is grown in association with other trees or crops.

Leaf phenology of woody species may have a bearing on leaf-fall and thus seasonal fluctuations in soil C stock of AFS involving such species. Even if evergreen and deciduous trees may have similar litterfall production on an annual basis despite having seasonal peaks/troughs in litterfall, trees that are leafless during the active growth phase of understory crops are particularly preferred in agroforestry. For example, poplar (*Populus deltoides*), a fast-growing deciduous tree, a popular agroforestry species in northern India, is leafless during the winter season when wheat is grown as an understory species (Figures 12.5, 12.6 and 12.7). The "reverse phenology" of the *Faidherbia albida* tree, a common agroforestry tree in the parkland system West African Sahel that has leaves in the dry season and is leafless during the rainy (cropping) season is too well known in agroforestry (Figure 14.4). The effect of such seasonal leaf falls on soil C dynamics and nutrient availability to the understory species remains little understood.

Differences in wood quality of trees vis-à-vis their C accumulation rates are also relevant in this context. Fast-growing species may accumulate more C before they are 10 years-old than slower-growing species; however, the slower-growing species accumulate more C in the long-term (Redondo-Brenes 2007). The wood of slower-growing species also possesses higher specific gravity, which further increases the CSP in the long-term (Baker et al. 2004; Bunker et al. 2005; Redondo-Brenes and Montagnini 2006). The more valuable, high-specific gravity wood also constitutes a longer-term sink for fixed C (e.g., construction timber, furniture, woodcrafts) than low specific-gravity wood used for short-lived purposes such as packaging cases and poles.

Nitrogen-fixing trees that constitute an important woody component of tropical AFS (Chapter 17) merit special mention in this context. Mixed plantings involving N_2-fixing tropical species have been reported to produce more aboveground biomass or volume production compared to their monocultures (Bauhus et al. 2004; Forrester et al. 2006; Kumar et al. 1998). Several studies comparing N_2-fixers and non-N_2-fixers have reported 20 to 100% more soil C under N_2-fixers (Binkley and Sollins 1990; Cole et al. 1995; Johnson 1992; Resh et al. 2002; Rhoades et al. 1997). Several studies on encroachment of woody plant species, mainly N_2-fixing tree legumes, into natural grass systems also showed significant increases in SOC (Pugnaire et al. 1996; Stock et al. 1995). These increases are attributed to greater inputs of N to N-limited ecosystems (Wardle 1992). Major differences in organic C inputs from tree prunings of N_2-fixing trees have also been reported; for example, on a 19-year-old study site, Oelbermann et al. (2006) noted significant differences in organic matter inputs between alley-cropped *Gliricidia sepium* and *Erythrina poeppigiana* in Costa Rica (see also Chapter 6). Thus, biomass and soil C sequestration in AFS could be influenced by selecting appropriate tree species. Another relevant factor is the influence of management practices on the formation and stability of soil aggregates, and thus the amount of carbon sequestration, as discussed in Section 20.3.5.

20.6.3 Mitigation and Adaptation Strategies

The most significant issues of agricultural and other land-use management in the context of climate-change discussions are mitigation and adaptation (M & A). As explained earlier (Section 20.2.5), mitigation refers to reducing climate change, while adaptation refers to "adapting to life in a changing climate." Thus,

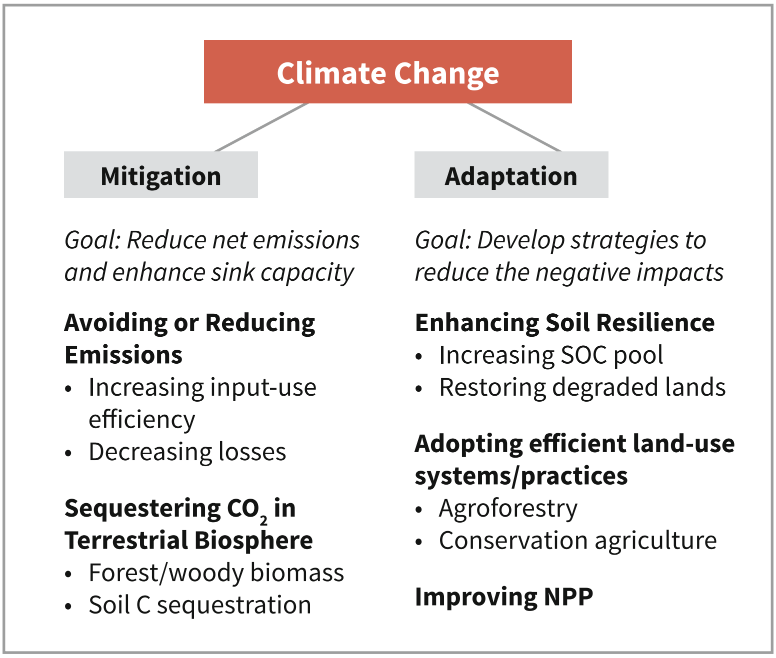


Figure 20.12 Climate change mitigation and adaptation (NPP stands for Net Primary Productivity)

while mitigation strategies are widely applicable, adaptation involves the "calibration" of technologies according to local needs and conditions. Although mitigation and adaptation are different concepts, the terms and action plans surrounding them (see Figure 20.12) are so related and intertwined that the terms are usually used collectively as M & A, and sometimes synonymously for one another. Several strategies have been suggested for addressing the two issues individually as well as together, the most prominent rallying themes are carbon sequestration for mitigation and "Climate Smart Agriculture (CSA)" for adaptation. "Climate Smart Soils" is another term proposed that emphasizes the implementation of soil-based greenhouse gas mitigation activities (Paustain et al. 2016). The concept involves the integration of the time-tested soil management practices of proven benefits, along with the quantitative assessment of the emissions and reductions associated with each, which, as the authors acknowledge, is a challenging task. Voluminous literature is available in various forms (online, print, etc.) on the numerous such adaptation strategies around the world.

20.6.4 Development Agendas and Paradigms

The focus of this chapter has been on explaining the fundamental principles and processes involved in climate change mitigation and examining how agroforestry can contribute to biological carbon sequestration, not to develop and implement programs to put the principles into practice or describe the numerous initiatives and on-going programs. The significant role that agroforestry can play in attaining carbon sequestration and, therefore, climate change mitigation figures prominently in almost all development agendas and paradigms related to land-use systems and their management. And, such agendas and paradigms are too many (as a simple Internet search will reveal) to be included here in a meaningful manner. Moreover, many of them are short-lived or transient rallying themes, and too broad in coverage such that items of direct relevance to agroforestry may have to be winnowed out of large heaps. Nevertheless, there are some recent (since about 2015) initiatives in carbon sequestration that are directly relevant to agroforestry and deserve to be mentioned, especially because of their apparent newness.

Soil Carbon Four per Mille (4p 1000): The reference is to an initiative launched by the French government in 2015 at the 21st Conference of Parties of UNFCCC as a multistakeholder platform aiming at increasing SOC storage through sustainable practices. Its name signifies the global importance of soils for climate change, based on the claim that an annual growth rate of only 0.4% of today's global soil organic carbon (SOC) stocks would have the potential to counterbalance the current increase in atmospheric CO_2. The proposal that has received some attention (e.g., Nath et al. 2018) has also been criticized as an aspirational goal with a rather poor definition of its numerical target (Rumpel et al. 2019).

MRV: Measurement, Monitoring, Verification, and Reporting on Carbon: The importance of applying stringent MRV schemes to soil organic carbon has been recognized but proven difficult, due to the high magnitude of measurement error. The reasons for the error include high spatial variability of soil properties and the lack of rigorous procedures for soil sampling and laboratory measurements (IPCC 2018). Smith et al. (2019) argue that since the organic carbon content of soils cannot easily be measured, a key barrier to implementing programs to increase soil organic carbon at a large scale is the absence of credible and reliable MRV platforms, both for national reporting and emissions trading.

One Trillion Trees Around the Globe: A global initiative was announced at the 2020 World Economic Forum, Davos, Switzerland, Jan 2020, to plant one trillion trees globally as a measure to promote carbon capture from the atmosphere and mitigate climate change. The scientific basis of the initiative is that planting a trillion trees could capture more than a third of all the greenhouse gases humans have released since the industrial revolution (Bastin et al. 2019). However, the claim that massive tree planting at the global level is the most effective climate change solution has been rebutted by Friedlingstein et al. (2019) who argue that the climate change mitigation potential of tree planting is an overestimate that is inconsistent with the dynamics of the global carbon cycle and its response to anthropogenic carbon dioxide emissions.

Carbon Farming: The term refers to a variety of farming methods organized around carbon sequestration in soils and plants. It is not an entirely new activity: several publications are available on the topic (e.g., Lin et al. 2013), and the Australian Government launched the Carbon Farming Initiative (CFI) in 2011 (Macintosh 2013). The role of agroforestry systems involving NDHP (non-destructively harvested perennial) species in carbon farming has, however, been highlighted recently by Toensmeier (2016), in his book *The Carbon Farming Solution.*

Regenerative Agriculture (RA): The term RA has attained considerable attention and prominence lately but still lacks a widely accepted definition. Lal (2020) describes it as encompassing "a wide range of farming and grazing practices aimed at restoration and sustainable management of soil health through sequestration of soil organic carbon." The author presents a schematic diagram including a wide range of land management issues and articulates that the basic tenets of RA are designed to draw carbon dioxide from the atmosphere, and specific packages of practices depend on site-specific biophysical environments and the human dimensions.

20.7 Concluding Remarks

Climate change and global warming became prominent global environmental issues around the 1990s. Following that, agroforestry became recognized as a land-management strategy with considerable potential for addressing those issues. The underlying scientific premise is that photosynthetic carbon capture by trees is an effective strategy for limiting the rise of CO_2 concentrations across the globe. The relatively higher efficiency of trees and other perennial species that are an integral part of agroforestry systems would help store atmospheric CO_2 and other greenhouse gases in the biomass and soils. Thus, agroforestry systems, compared with treeless agricultural systems, would lead to higher rates of carbon sequestration, i.e., removal of carbon from the atmosphere and its storage in soils and plants for longer periods.

Soils play a vital role in the global C cycle. The total soil C is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg. Any change in soil C pool would have a significant effect on the global C budget. In general, the soil carbon sequestration potential (SCS) of the common land-use systems is in the order forests> agroforests> tree plantations> arable crops.

Soil aggregates and size fractions have an important effect on the retention of C in soil. Aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic substances. The smallest size fractions among the microaggregates (smaller than 53 μm in diameter, usually referred to as the silt+clay fraction) are composed of recalcitrant organomineral complexes. These are bound together in larger microaggregates that range from 53 – 250 μm in diameter and are held together with polysaccharides and humic materials that are also persistent due to biochemical recalcitrance and physical protection. Macroaggregates are greater than 250 μm in diameter. These three size classes occur in what is referred to as an aggregate hierarchy. Soil type, climate, landscape position, ecology, and anthropogenic factors all play a major role in aggregate formation and soil carbon sequestration.

The extent of carbon sequestration in AFS is assessed by direct measurement or estimation using formulas and computer models of C present in both biomass (above and belowground) and soils. The aboveground values of C sequestration are mostly direct derivatives of biomass measurements and, therefore, their estimates are relatively more accurate, precise, and straightforward than belowground (soil) values. Various methods used to assess the soil C stock include laboratory determinations, isotopic measurements, spectroscopic method, and use of computer models; the C stock estimates vary greatly depending on several factors, including biophysical and socioeconomic characteristics of the system parameters, as well as the study procedures. Besides, carbon dating procedure that is used to determine the "age" or date of the carbon is also used, though rarely, in agroforestry.

The research results obtained so far have shown that agroforestry systems store higher amounts of carbon, compared to single species cropping and grazing systems, in both aboveground and belowground compartments of the system, and particularly in soil depths below 50 cm. Soils under agroforestry systems have relatively higher proportions of microaggregates in the lower soil layers, suggesting higher levels of C sequestration. The extent of C sequestration will depend on several site-specific factors as well as system management. The aboveground C sequestration rates in AFS around the world vary from 0.3 to 15.0 t ha^{-1} yr^{-1}, and the soil C stock is in the range of 30 to 300 t ha^{-1}. The best-bet estimates of the ranges of soil C sequestration are 5–10 kg C ha^{-1} in about 25 years in extensive tree-intercropping systems of arid and semiarid lands to 100–250 kg C ha^{-1} in about ten years in species-intensive multistrata shaded perennial systems and homegardens of humid tropics.

In general, the methods used for the determination of C sequestration in agroforestry systems have some inherent weaknesses to varying degrees resulting from inaccuracies related to field-sampling procedures, assumptions made, methods of computations, data interpretations, and so on. These are not problems that are unique to agroforestry, however. Some meta-analyses have been conducted to compare and synthesize results from different studies and identify common patterns, discrepancies, or other interesting relationships. The results showed that overall AFS increased the SOC stocks up to 100 cm soil depth in the tropics, but not always in the temperate regions. The extent of AFS-induced SOC storage varied significantly across agroecological regions, age of the system, soil depth, and ecological (climatic and soil) conditions. Furthermore, the potential role of AFS in climate change mitigation through SOC improvement could be more relevant in the tropical regions where the soils are known to be C-depleted than in the C-saturated temperate soils.

Most discussions on C sequestration also emphasize the importance of management practices on C sequestration, especially in soils. It is known that best management practices, including agroforestry, can restore at least some of the carbon that is lost over the decades or centuries due to land cultivation. The predictions on the effects of management practices, however, are based on the expected effects of such practices on biomass productivity of the system's components, particularly for trees grown in plantations. Such results from stands of single species may not have much relevance to C sequestration in agroforestry systems involving that species grown in association with other trees or crop species. Carbon sequestration potentials of tropical tree taxa are, indeed, highly variable. The choice of tree species and patterns of species admixture are, nevertheless, important considerations about C sequestration in agroforestry systems. Despite the lack of an abundance of rigorous and long-term research data, this perception is supported by the scientific foundations upon which it is based and the new evidence that keeps coming, including the results of meta-analyses. Thus, the adoption of agroforestry practices can be a safe bet for carbon sequestration and climate change mitigation. Indeed, it is quite appropriate that agroforestry figures prominently in such debates happening in many parts of the world.

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Agroforestry for Biodiversity Conservation

21

Contents

Abstract

Biological Diversity, or biodiversity, refers to all living things and the interactions among them, including the diversity within species, between species, and of ecosystems. Agricultural biodiversity or agrobiodiversity is a subset of biodiversity including all crops and livestock and all interacting species of pollinators, symbionts, pests, parasites, predators, and competitors. This remarkable *Gift of Nature* is being threatened and wantonly destroyed through human activities such as tropical deforestation, leading to disastrous ecological consequences. Agroforestry systems (AFS), which traditionally harbor far more species diversity than conventional agricultural and plantation forest ecosystems, are also experiencing species losses through a process of simplification, e.g., the transformation

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of shaded coffee and cacao production systems into unshaded crop monocultures with intensive management leading to *agro-deforestation.* Most tropical AFS, especially the multistrata systems, are outstanding loci for biodiversity conservation and are intrinsically capable of promoting both aboveground and belowground biodiversity. Genetic diversity, another dimension of species diversity, refers to genetic (intra-specific) variations among crop and tree populations; many landraces of crop plants and genetically diverse tree populations occur in AFS. The pathways proposed for conservation of tree diversity in smallholder AFS include *in situ* (maintenance of tree diversity in the wild forest), *ex-situ* (preservation of trees in seed banks, seed stands, botanical gardens, and field trials), and *circa situm* (preservation of planted and/or relic trees in farmland where natural forest containing the same trees existed once) approaches. Agricultural landscapes with substantial agroforestry activities are effective for the conservation of biodiversity in managed ecosystems and play a significant role in conserving and even enhancing biodiversity from farms to the landscape level.

21.1 Introduction

The concept of ecosystem services and the general considerations about the role of agroforestry in providing various ecosystem services have been presented in Chapter 19. As discussed therein, climate change mitigation and biodiversity conservation are recognized as the two major ecosystem services provided by agroforestry systems. The previous chapter (Chapter 20) focused on the former (climate change mitigation); this chapter will focus on biodiversity conservation along with the related issue of ecosystem resilience. Even before attaining its current status as a topic of such global prominence, biodiversity has been a major area of ecological and environmental interest, and a voluminous body of literature is available on its principles and practices. The elucidation of those principles and review of the developments in the subject will be limited in this chapter to the extent deemed necessary to provide the background for discussing their relevance and scope for adoption and application in agroforestry.

21.2 Biodiversity Conservation: A Major Global Environmental Issue

The importance of biodiversity for the very survival of the planet and the welfare of the current and future generations of its inhabitants is increasingly being recognized the world over. At the same time, this remarkable Gift of Nature is being threatened and wantonly destroyed at alarming rates. For example, as mentioned in the first chapter of this book (Chapter 1, Figures 1.7, 1.8, and 1.9), the successive reports by FAO and other international organizations (e.g., FAO/UNEP 2020) have highlighted the massive biodiversity loss and other disastrous consequences of the destruction of tropical forests that has continued at an annual rate of about one percent for the past several decades. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, another intergovernmental body related to biodiversity; see Chapter 19) has concluded that "nature is declining globally at rates unprecedented in human history" and that around one million animal and plant species are now threatened with extinction, many within decades. The direct factors contributing to such losses are many: land-use changes and the associated alteration and degradation of ecosystems and loss of habitats, overexploitation of species, illegal trade in wildlife, invasive alien species, environmental pollution and contamination, global climate change, and so on (Rands et al. 2010; IPBES 2019). Recognizing the danger of an imminent "mass extinction" of species and the need to conserve them, a major global initiative called the *Convention on Biological Diversity* (CBD) was launched at the UN Conference on Environment and Development (the Rio "Earth Summit") held in Rio de Janeiro, Brazil, in June 1992 [where the UNFCCC (United Nations Framework

Convention on Climate Change) treaty was also adopted as mentioned in Chapter 20 (Section 20.2.4)]. The CBD represents the global community's commitment to "*the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from the use of genetic resources*" (https://www.cbd.int/history/). To commemorate the adoption of the final text of the Convention, the UN General Assembly has since adopted May 22nd as *International Day for Biological Diversity*. Sadly, despite these symbolically impressive global initiatives, biodiversity decline continues unabated in many parts of the world.

21.3 What is Biodiversity?

Article 2 of the CBD defines *Biological Diversity* as "the variability among living organisms from all sources including, *inter alia,* terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems." The term was first used by J. Arthur Harris in a 1916 article titled "The Variable Desert" (Harris 1916) in *The Scientific Monthly* – a periodical that merged into *Science* in 1958. The euphonious word *biodiversity*, however, was introduced to the scientific literature by the American biologist Elliot A. Norse in a 1980 US government report. Gradually, the term attained acceptance in scientific usage and has become widely and increasingly used in scientific and technical publications as well as in journalistic and common parlance since 2000 (Thompson and Starzomski 2007).

21.3.1 Biodiversity: Definitions Galore

As a contracted form of biological diversity, biodiversity has been defined variously by different authors. Some examples are given below:

Sandlund et al. (1992): Structural and functional variety of life forms at genetic, population, community, and ecosystem levels.

DeLong (1996): A state or attribute of a site or area, specifically referring to the variety within and among living organisms, assemblages of living organisms, biotic communities, and biotic processes, whether naturally occurring or modified by humans.

Dyke (2008): Biodiversity means different things to people from differing backgrounds. In natural history usage, it represents the biotic elements of nature that can be described and classified; environmental activists view it as an inherent value-laden feature of natural systems; and, to conservation biologists, biodiversity is a quantifiable attribute pertinent to an understanding of community structure, environmental processes, and ecosystem functions.

Mayer (2006): Before we attempt a definition of biodiversity, we must recognize the *thought styles* and philosophical commitments that are entangled in the concept and affect the definition that we choose.

Given that biodiversity refers to all living things and the interactions between them, it can be observed and measured at any spatial scale ranging from microsites and habitat patches to the entire biosphere. Biodiversity can also be determined in terms of genetic diversity and the identity and number of different types of species, assemblages of species, biotic communities and processes, and the quantity (e.g., abundance, biomass, cover, rate) and structure of each (DeLong 1996). It is also recognized at different organizational levels as:

- ***Species diversity***: indicates how many divergent organisms occur in a particular area (biodiversity often being perceived as species diversity).
- ***Genetic diversity***: quantifies the extent of heritable variations within a population. The persistence of organisms can be severely stressed, even when they are not extinct if genes that confer specific survival traits such as disease resistance or environmental tolerance are lost owing to habitat loss/fragmentation or other effects that decrease population size.
- ***Ecosystem diversity* or *ecological diversity***: refers to the variety and variability of communities or habitats that exist in a given

geographical area. Ecosystem diversity is sometimes difficult to assess as the boundaries of some communities or habitats gradually merge with the adjacent ones over a gradual *ecotone* or transition zone (https://www.uwgb.edu/biodiversity/about/biodiversity.asp).

Biological diversity involves two elements: *Species Richness* and *Equitability* or *Evenness*.

Species Richness: The term, coined by McIntosh (1967), is the oldest and the most intuitive measure of biodiversity (Magurran 2004). It refers to the number of species in the *community* and is defined as an "assemblage of populations of organisms in a given area" (DeLong 1996). As a measure of diversity, species richness has several merits (Dyke 2008): ease of data collection (sometimes limited to recording whether the species is present or absent); ease of presentation, interpretation, and comparison with other similar communities; and the number of species present offers a useful first approximation of the biodiversity of the area or habitat. This approach, however, does not provide information on the relative or absolute abundance of individual species in the community, whether the species present are equitable in numbers or distribution, or whether the community is composed of a few abundant and many rare species.

Equitability* or *Evenness denotes the relative abundance of different types of items in an area (i.e., evenness in the contribution of different species to the community).

Both species richness and evenness are commonly combined into a concept of diversity. Consistent with this, Hubbell (2001) stated that biodiversity is "synonymous with species richness and relative species abundance in space and time."

21.3.2 Measuring Biodiversity

Several quantitative indexes have been developed to quantify diversity, popularly known as *diversity indexes* (or *indices*). Tables 21.1 and 21.2 provide a summary of the major such indexes and some examples of their applications in agroforestry. Although developed two-to-three or more decades ago, these indexes are still widely used in ecology. Besides, many complex *species abundance models* exist (see Magurran 2004). Several of the diversity indexes are based on the proportional or relative abundance of species and are used to characterize diversity in agroforestry (explained later in this chapter). Peet (1974) describes such indexes as *heterogeneity indexes* as they take both evenness and species richness into account. Southwood (1978) termed them as *non-parametric indexes* as there are no implicit assumptions about the shape of the underlying species distribution pattern.

Broadly, diversity indexes fall under two categories (Table 21.1): *indexes derived from information theory* (e.g., Shannon index, Brillouin's diversity index, etc.) and those based on *dominance measures* (e.g., Simpson's index, McIntosh measure of diversity). The most widely used measures of diversity, however, are the information theory-based indexes. As indicated by Magurran (1988), these indexes are based on the rationale that the diversity, or information, in a natural system can be measured like the information contained in a code or message. Conversely, the heterogeneity indexes based on dominance are weighted toward abundances of the commonest species rather than providing a measure of species richness. Dyke (2008) noted that such indexes generally symbolize *some features* of biodiversity and not *biodiversity per se*. The units of diversity, such as genetic, community, and ecosystem diversity, do exist and are sometimes utilized, depending on the conservation objective. To be meaningful to the conservation biologists, however, it is important to specify what feature of biodiversity is being studied, at what level, and at what dimension of that level. In that context, three levels of diversity have been recognized (Whittaker 1960, 1972, 1975; Peet 1974; Vane-Wright et al. 1991). These are (1) *alpha* or *within-habitat diversity*, (2) *beta* or *between-habitat diversity,* and (3) *gamma* or *landscape-level diversity* for a geographical area – a composite of alpha and beta diversity. Although the three types of diversity can change independently of one another, in real ecosystems, they are often correlated (Dyke 2008).

Alpha Diversity: Popularly known as *biodiversity indexes* or simply as *diversity indexes,* this refers to the diversity of species within an

Table 21.1 Commonly used indexes of alpha (community) species diversity and their associated formulae

Index	Formula	Descriptions, Distinctions, and Equation terms	Source	Examples of agroforestry applications
Information Statistics Indexes				
Brillouin's diversity index, *HB*	$HB = \frac{\ln(N!) - \sum_i \ln(n_i!)}{N}$	Brillouin's *HB* is recommended for fully censused communities and is considered free from statistical error. It rarely exceeds a value of 4.5. Although the proportions remain constant, its value changes when species numbers increase. N = total number of individuals; n_i = number of ith species at site	Pielou (1969, 1975)	Peroni and Hanazaki (2002)
Brillouin's maximum diversity index, HB_{max}	$HB_{max} = \frac{1}{N}\ ln\ \frac{N!}{\left\{\left\lfloor\frac{N}{S}\right\rfloor!\right\}^{s-\gamma}\cdot\left\{\left(\left\lceil\frac{N}{S}\right\rceil+1\right)!\right\}^{\gamma}}$	HB_{max} represents the maximum diversity possible with a given sample size and species richness. $\left\lceil\frac{N}{S}\right\rceil$ = the integer of $\frac{N}{S}$ and $\gamma = N - S\left\lceil\frac{N}{S}\right\rceil$	Magurran (1988, 2004)	na
Brillouin's evenness index, *HBe*	$HBe = HB/HB_{max}$	Based on Brillouin's *HB* and HB_{max}. It is not an estimate but an accurate statistic. While it is more difficult to compute than most diversity indices, *HBe* reduces the sensitivity of the estimate to changes in species density	Pielou (1969, 1975)	Hidayat et al. (2018)
Hill's diversity index, H_1	$H_1 = \exp\left[-\sum(p_i \ln p_i)\right]$	An exponential form of the Shannon index and signifies the relation between the species-richness indices and the evenness-indices. Although widely used, it is sensitive to single-species dominance	Hill (1973)	Santoro et al. (2020)
Hill's reciprocal of C, H_2	$H_2 = \frac{1}{C} = \left(\sum_i p_i^2\right)^{-1}$	The reciprocal of the Simpson index (C); commonly used along with Hill's H_1, but is not as dependent on the number of species as is H_1	Hill (1973)	na
Margalef's diversity index, *DMg*	$DMg = \frac{(S-1)}{\ln(S)}$	A widely used index, it is easy to calculate but best employed on large sample sizes	Margalef (1968)	Asigbaase et al. (2019)
Pielou's index of evenness, *E*	$E = \frac{H'}{\ln S} = \frac{-\sum_i p_i \ln p_i}{\ln S}$	*E* is the ratio of observed diversity [H'] to the maximum possible diversity of a community with the same species richness [H'max]. Mathematically relates evenness and richness, which are not necessarily related biologically	Pielou (1969)	Abebe et al. (2013)
Probability of interspecific encounter, *PIE'*	$PIE' = 1 - \sum_i p_i^2$	*PIE'* complements the Simpson diversity index ($1 - C$), and estimates diversity instead of dominance	Baev and Penev (1995)	Heer et al. (2015)
Shannon index, H'	$H' = -\sum(p_i \ln p_i)$	Perhaps the most popular diversity index, Shannon index is used for both large and small sample sizes. Also known as Shannon-Weaver diversity index. Useful method for	Shannon and Weaver (1949)	Villanueva-López et al. (2019)

(continued)

Table 21.1 (continued)

Index	Formula	Descriptions, Distinctions, and Equation terms	Source	Examples of agroforestry applications
		comparing the diversity of different habitats, especially when a number of replicates have been taken (Magurran 2008)		
Dominance Measures				
Simpson index, *C*	$C = \sum_i p_i^2$	The Simpson index (C) provides indicates of dominance, while Simpson diversity index ($1 - C$) is a measure diversity. It represents the probability of any two individuals drawn randomly from an infinitely large community belonging to different species	Simpson (1949)	Kumar (2011)
McIntosh measure of diversity, *D*	$D = \frac{(N-U)}{N-\sqrt{N}}$	A community is envisaged as an S dimensional hyper volume and that the Euclidean distance of the assemblage from the origin can be used as a measure of diversity McIntosh U index, $U = \sqrt{\sum n_i^2}$	McIntosh (1967)	Wang et al. (2018)
Berger-Parker index, *d*	$d = \frac{N_{max}}{N}$	An intuitively simple and easy to calculate dominance measure. It measures the proportional abundance of the most important species. Just as Simpson index, the reciprocal form represents diversity. N_{max} = the number of individuals in the most abundant species	Berger and Parker (1970)	Labrière et al. (2015)

Source: Modified from Dyke (2008) with some additions from Magurran (1988) and other sources mentioned

Note 1: While the specific terms of the equations are described in column 3 against each item, the more general terms are explained here: N = total number of individuals; p_i = percentage of ith species at site; n_i = number of ith species at site; S = number of species at site; H_1, H_2 = Hill's diversity numbers

Note 2: Worked out examples for some of these indexes (e.g., Shannon, Brillouin, Simpson, McIntosh and Berger-Parker indexes) are available in Magurran (1988)

Note 3: The examples mentioned in the last column may represent more than one index

na=not available

ecological community, or "the species richness of standard site samples" (Vane-Wright et al. 1991). Whittaker (1972) posited that diversity in the strict sense is richness in species, and is appropriately measured as the number of species in a sample of standard size. A *species list*, indicating the total number and names of species at a particular site, is the simplest measure of this. An improvement of the species list, however, is a measure of species richness, which is normalized to reflect the number of species recorded per sampling area or a uniform number of observations. Alpha diversity, thus, is a measure of two attributes: species richness and species evenness. Dozens of different measures of α diversity are available in the literature. Table 21.1 lists two categories of such metrics: *Information Statistics Indexes* and *Dominance Measures*.

Beta Diversity: According to Whittaker (1972), β diversity represents "the extent of species replacement or biotic change along

Table 21.2 Commonly used indexes of β and γ diversity and their associated formulae

Index	Formula	Descriptions, Distinctions, and Equation terms	Source	Examples of agroforestry applications
β diversity indexes				
Whittaker's measure, β_w	$\beta_w = \frac{S}{\overline{\alpha}}$	The first and one of the most direct measures of β diversity; S= the total number of species recorded in the systems (i.e., gamma diversity) and $\overline{\alpha}$ =the average sample diversity where each sample is a standard size and diversity is measured as species richness	Whittaker (1960)	Yu and Sun (2013)
Cody's measure, β_c	$\beta_c = \frac{g(H)+l(H)}{2}$	Developed to reflect the change in composition of bird communities along habitat gradients. Easy to calculate and provides a good intuitive measure of species turnover; $g(H)$=the number of species gained along the habitat transect and $l(H)$=the number of species lost over the same transect	Cody (1975)	Zhu et al. (2007)
Routledge's measure, β_R	$\beta_R = \frac{S^2}{(2r+S)} - 1$	Takes into consideration the overall species richness and the degree of species overlap; S= the total number of species in all samples; r= the number of species pairs with overlapping distributions	Routledge (1977)	na
Routledge's measure, β_I	$\beta_I = \log(T) - \left[\left(\frac{1}{T}\right)\sum e_i \log e_i\right] - \left[\left(\frac{1}{T}\right)\sum S_j \log S_j\right]$	Based on information theory and has been simplified for qualitative data and equal sample size (Wilson and Shmida 1984); e_i=the number of samples in the transect in which species i is present; S_j=species richness of sample j; and T=$\sum e_i = \sum S_j$.	Routledge (1977); Magurran (2004)	na
Routledge's measure, β_E	$\beta_E = \exp \beta_I$	Exponential form of β_I.	Routledge (1977)	na
Wilson and Shmida's measure β_T	$\beta_T = \frac{[g(H)+l(H)]}{2\alpha}$	This measure of β diversity has the same elements of species los (l) and gain (g) that are present in Cody's measure and the standardization by average sample richness α, which is a component of Whittaker's measure	Wilson and Shmida (1984)	Shackleton (2000)
Similarity coefficients				
Jaccard similarity coefficient, C_J	$C_J = \frac{a}{a+b+c}$	One of the most useful and widely used indexes of the 60 or so similarity indices for binary data (Birks 1987); a = the total number of species present in **both** samples; b = the number of species present **only** in sample 1; and c = the number of species present **only** in sample 2	Jaccard (1912)	Sistla et al. (2016)

(continued)

Table 21.2 (continued)

Index	Formula	Descriptions, Distinctions, and Equation terms	Source	Examples of agroforestry applications
Sørensen similarity coefficient, C_S	$C_S = \frac{2a}{2a+b+c}$	C_S is analogous to the Jaccard measure. Terms in the equation are also the same. Southwood and Henderson (2000) regards C_S as one of the most effective presence-absence similarity measures. Both C_S and C_J are simple and easy to use but qualitative in character and based on presence-absence data. The coefficients do not take account of the abundance of species; in fact, they count all species equally regardless of whether they are abundant or rare	Sørensen (1948)	Kumar et al. (1994)
Sørensen quantitative, C_N	$C_N = \frac{2jN}{(N_a+N_b)}$	C_N is perhaps the most widely used version of the Sørensen's index and it is based on quantitative data (Southwood 1978); $jN=$ the sum of the lower of the two abundances recorded for species found in both sites; $N_a=$ the total number of individuals in site A; $N_b=$ the total number of individuals in site B	Bray and Curtis (1957)	Negash et al. (2012)
Morisita–Horn index, C_{MH}	$C_{MH} = \frac{2\sum(a_i \cdot b_i)}{(d_a+d_b)*(N_a*N_b)}$	C_{MH} also takes species abundances into account. It is influenced by species richness and sample size. But is sensitive to the abundance of the dominant species. A disadvantage, however, is that it is highly sensitive to the abundance of the most abundant species; $N_a =$ the total number of individuals at site A; $N_b=$ the total number of individuals at site B; $a_i =$ the number of individuals in the ith species in A; $b_i =$ the number of individuals in the ith species in B; and d_a (and d_b) are calculated as follows: $d_a = \frac{\sum a_i^2}{N_a^2}$ and $d_b = \frac{\sum b_i^2}{N_b^2}$.	Magurran (2004)	Pinoargote et al. (2017)
γ-diversity indexes				
Gamma diversity, γ	$\gamma = dS/dD\left[\frac{g+l}{2}\right]$	γ-diversity is the total species diversity in a landscape. It is the product of α and β diversity. Unlike beta diversity, gamma diversity is independent of habitat and is calculated as the rate of change of species composition with respect to distance; D is the distance over which species turnover occurs; g and l are respective rates of species gain and loss	Dyke (2008)	DaRocha et al. (2016)

Source: Compiled from Magurran (1988, 2004) and other sources mentioned
Note 1: Worked out examples for all the 10 indexes mentioned above are available in Magurran (1988)
Note 2: The examples mentioned in the last column may represent more than one index
na=not available

environmental gradients." Also known as "beta richness," it represents the degree of change in species composition of communities along a gradient and quantifies the rate of change in species composition in communities across a landscape. Dyke (2008) suggests that beta diversity provides a first approximation of area diversity or regional diversity. Table 21.2 describes six of the prominent measures used for computing β diversity. One of the easier and most intuitive approaches for describing the β diversity of pairs of sites is to use a similarity/dissimilarity coefficient (Magurran 2004). Numerous similarity indexes also have been proposed; four prominent ones are presented in Table 21.2. The most useful ones are also some of the oldest measures such as the Jaccard index and Sørensen index (Southwood 1978).

Gamma Diversity refers to the diversity of species across larger landscape levels. Specifically, it denotes the diversity of different kinds of communities within a landscape. Conceptually, it is "the rate at which additional species are encountered as geographical replacements within a habitat type in different localities" or "a species turnover rate with the distance between sites of similar habitat, or with expanding geographic areas" (Cody 1986). Gamma diversity is the product of alpha diversity of a landscape's communities and the degree of beta differentiation among them (Vane-Wright et al. 1991).

As mentioned above, many diversity indexes are used in agroforestry research (Tables 21.1 and 21.2). Some of the more commonly used ones include the Shannon index (also known as Shannon-Wiener index or Shannon–Weaver index), Margalef's diversity index, Simpson index, McIntosh measure of diversity, Jaccard similarity coefficient, and Sørensen similarity coefficient.

21.4 Agrobiodiversity or Farmland Biodiversity

Agricultural biodiversity or agrobiodiversity, which is also synonymous with farmland biodiversity, is an important subset of biodiversity and has attracted considerable scientific attention (e.g., Wood and Lenne 1999; Butler et al. 2007; Andersen 2008; Wall et al. 2012). The interdependence between biodiversity and agriculture is perhaps as old as agriculture itself, and it is now well recognized that all farmland biodiversity is critical to maintaining sustainable agroecosystems. Qualset et al. (1995) defined agrobiodiversity as including all crops and livestock and their wild relatives, and all interacting species of pollinators, symbionts, pests, parasites, predators, and competitors. FAO (1999) further explained it as the variety and variability of animals, plants, and microorganisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry, and fisheries. In addition to the range of genetic resources (crop varieties, animal breeds, etc.) and species exploited for food, fodder, fiber, fuel, and pharmaceuticals, agrobiodiversity encompasses the entire gamut of non-harvested species of soil microbes, predators, and pollinators that sustain production and support the agricultural, pastoral, forest, and aquatic ecosystems. It thus includes a diverse suite of organisms ranging from insects, earthworms, and soil microbes, providing key ecosystem services from - pollination of crops and decomposition of soil organic matter to the farmland birds that enable seed dispersal and pollination (Chapter 22).

While it is generally accepted that greater biodiversity contributes to the resilience of the agroecosystems (see Section 21.7), farmland biodiversity is declining owing to the intensification of agriculture. Furthermore, the interactions of "food agrobiodiversity" with other components of agrobiodiversity within agricultural ecosystems involving pests, pathogens, pollinators, and so on, are also significant, as they affect food production. These interactions may be direct, as with insects devouring crops, or indirect, through the modification of agroecosystem function (Wood and Lenne 1999). There are also complex interactions with the wild, including the transfer of pollen and seed from wild relatives into agroecosystems, and the migration of pests, pathogens, predators, and weeds: these too impact directly on food production and agroecosystem functions (Chapter 22).

Swift and Anderson (1994) grouped the biotic components of agroecosystems into three broad types based on the role they perform in ecosystem functioning: *productive, beneficial (resource),* and *destructive*. Productive biota includes crop plants and livestock, producing food, fiber, or other products for consumption/trade. Beneficial biota favors the productivity of the system and includes pollinators, plants of fallows, and the soil biota regulating nutrient cycling. Destructive biota comprises weeds, pests, and pathogens. The birds perching on trees in agroforestry and other tree-based systems, and the wild animals (e.g., primates and elephants) from adjacent forest areas may also damage crops and thus fall under the category of destructive biota. As highlighted by Swift and Anderson (1994), this classification underpins management – the role of farmers and farm scientists in increasing crop and animal production by favoring the beneficial biota and discouraging the destructive ones. While biodiversity is critical to sustaining agriculture, agriculture could contribute to the conservation and sustainable use of biodiversity as is the case with agroforestry.

Erosion of farmland biodiversity: The traditional "biodiverse" agroecosystems, apart from being harbingers of farmland biodiversity, are fundamental to the livelihoods of many indigenous communities (Bucheli and Bokelmann 2017). Diversified production, especially in the smallholder production systems of the tropics, also aids the households to alleviate market risks (Jamnadass et al. 2013). Ecological literature is also replete with reports on species losses from agroecosystems owing to production intensification (e.g., the decline of pollinator populations; IPBES 2016). The bottom-line is that agricultural transformations may have devastating effects on the occurrence of disparate assemblages of species on farmlands. This is because agricultural intensification and specialization of farming have led to a simplification of agricultural landscapes and a loss of "(semi-)natural habitats" (Hendrickx et al. 2007). Agroforestry systems, which traditionally harbor far more species diversity than conventional agricultural and plantation forest ecosystems, are also experiencing species losses through a process of simplification. Examples include commercialization of the tropical homegardens (Abdoellah et al. 2006), a global decline in shade tree cover particularly in the coffee agroecosystems (Jha et al. 2014) and the preferential planting (5.4 times more often than native trees) of exotics such as *Grevillea robusta* as shade trees in the coffee agroforestry landscape of the Western Ghats, India, a global biodiversity hotspot (Nath et al. 2016).

As mentioned, transforming the shaded coffee and cacao production systems into unshaded crop monocultures characterized by intensive management may adversely affect agrobiodiversity. For example, the transient character of shade plants in cacao agroforestry beginning with temporary shade plants and its eventual transformation into mostly or completely unshaded monocultures in major cocoa-producing countries of Latin America is a profound environmental hazard (Tscharntke et al. 2011). Jha and Dick (2010) observed a decrease in native bee pollination with increased management intensity in coffee systems in Mexico, and several other studies confirmed more healthy coffee plants and fruits in less intensively managed coffee systems (Larsen and Philpott 2010), implying a reduction in ecosystem services following agricultural intensification. It is, thus, clear that the traditional tree-rich agroforestry systems in many parts of the world have been declining. In some parts of the Asia-Pacific region, this phenomenon is referred to as *agro-deforestation*, i.e., "the removal of trees or de-emphasis on the planting and/or protection of trees in the context of existing agroecosystems" (IPBES 2018).

21.5 Other Subsets of Biodiversity

Biocultural Diversity: A term of contemporary origin, it has been defined as the "diversity exhibited by interacting natural systems and human cultures" (https://www.ipbes.net/glossary/biocultural-diversity). Indeed, people living in diverse regions have used their traditional knowledge systems to utilize and/or conserve local natural resources. Biologists, anthropologists, and sociologists have also studied aspects relating to diversity for long and advanced many concepts and theories regarding the profound inter-linkages between nature and culture. According to Loh and Harmon (2014), nature and culture are "dual aspects of a single entity, biocultural diversity" and in recent years, there is increasing recognition that problems in nature and society are interrelated. This has led to the notion of Coupled Natural and Human Systems (CNHS), which focuses on interdisciplinary analyses of relevant human and natural system processes and their complex interactions at diverse scales.

Ethnobiodiversity or Ethno-cultural Diversity: This small and somewhat neglected component of biocultural diversity, refers to the complex interactions between the genetic diversity of wild and domesticated organisms and that of needs, tastes, and preferences of domesticators and (traditional) breeders/users (Szabó 1999). Many traditional societies around the world display considerable diversity in the ethnic characteristics that generally support *in situ* protection of biodiversity (Chapter 22, Section 22.4). A brief description of the incorporation of medicinal and aromatic plants in indigenous agroforestry systems is included in Chapter 11, Section 11.3.3.

21.6 Agroforestry for Biodiversity Conservation

21.6.1 Biodiversity Hotspots and "Coldspots"

The concept of "Biodiversity hotspots" has been a rallying theme for conservation efforts, especially for directing international funding and philanthropy; indeed, the conservation fraternity recognizes this as some sort of triage to focus their energies on. The term "biodiversity hotspot" was coined by Myers (1988) to denote regions of the world with unusually high concentrations of endemic species that suffer severe habitat destruction. Today, the term is applied more loosely as a measure of the perceived biological quality of high species richness. Myers et al. (2000) argued that "44% of all species of vascular plants and 35% of all species in four vertebrate groups are confined to 25 hotspots comprising only 1.4% of the land surface of the Earth." Recognizing and protecting such biodiversity hotspots has since become the reigning conservation paradigm. Around the world, as of 2020, there are 36 areas, which qualify as hotspots (https://www.conservation.org/How/Pages/Hotspots.aspx). Although representing only 2.4% of the Earth's land surface, they contain more than 50% of the earth's endemic plant and nearly 43% of bird, mammal, reptile, and amphibian species.

The hotspot concept has grown so popular within the wider conservation community that it has probably eclipsed all other approaches. Kareiva and Marvier (2003) argue that the concept leaves out vast expanses of the globe with considerable biological diversity "in the cold" – the so-called biodiversity "coldspots." The hotspot approach focuses on the proportion of natural flora that has been annihilated, and, to meet the criteria as a hotspot, a region must have suffered a loss of at least 70 % of the primary vegetation. Kareiva and Marvier (2003) proposed that rather than trying to classify high concentrations of species on a map, the conservationists should be more flexible and should be prepared to reward effective actions on the ground as they happen.

21.6.2 Agroforestry for Offsetting Threats to Agrobiodiversity

Most tropical agroforestry systems, especially the multistrata systems (see chapters 7 and 8), are outstanding loci for biodiversity conservation. Dubbed as "biodiversity coldspots," they serve as "stepping stones and refuges" for conservation and enhancement of diversity (Bhagwat et al. 2008; Negash et al. 2012). Being *biodiverse* systems, the CBD Strategic Plan (CBD 2010) suggests that land-use practices such as agroforestry will continue to play a major role in conserving and even enhancing biodiversity from farms to the landscape level in both tropical and

Figure 21.1 Multifunctional landscapes of central Java, Indonesia. Crop fields, residential areas, and woodlots juxtaposed to one another provide food and nutritional security, support livelihood options, and maintain agrobiodiversity and ecological functions besides sustaining cultural, aesthetic, and recreational needs. In comparison with the monocultural farming landscapes, these farming activities that are based on the land-sharing philosophy integrate the production and conservation objectives and fulfill a wider range of sociocultural needs and aspirations of the local population. (Photo: BM Kumar)

temperate regions of the world, as part of a multifunctional landscape (Figures 21.1 and 21.2) that are capable of providing a wide range of products and services. Bringing conservation measures to such landscapes will be a step in the right direction. Yet, they received little or no attention from a conservation perspective. Landscape-scale studies for understanding the dynamics of community structure and species interactions in human-dominated landscapes are also scarce. Tscharntke et al. (2012) proposed a framework consisting of eight hypotheses to analyze biodiversity in human-modified landscapes and to encourage more systematic research on its dynamics.

Agroforestry is intrinsically capable of promoting both above- and below-ground biodiversity and it is perhaps next only to natural forests in terms of species diversity and richness (e.g., complex multi-strata systems). Many traditional land-use systems are characterized by a great diversity of species with several life-forms as described in Chapters 7 and 8. Noble and Dirzo (1997) showed that forest gardens in Sumatra and West Kalimantan, Indonesia, including jungle rubber (rubber agroforestry systems of southeast Asia with a high concentration of rubber trees, *Hevea brasiliensis*, replacing fallows), with low management intensity, have 50–80% of the diversity of comparable natural forest (e.g., damar agroforestry gardens in Sumatra, Indonesia; Figure 7.10). In another case study on abundance, richness, and diversity of dung beetles and terrestrial mammals across a land-use gradient from plantain monoculture through cacao and banana agroforestry systems to forests in Talamanca, Costa Rica, Harvey et al. (2006) found that indigenous agroforestry systems provide suitable habitat for several forest-dependent species. Tsonkova et al. (2012) also found that in temperate alley cropping, the numbers of both the species and the individuals were much higher than in

Figure 21.2 The multistrata tropical homegardens in Tripura in the Northeastern Hill region of India are another excellent example of the multifunctional agroforestry landscapes. Similar to the various homegardens described in Chapter 7, these smallholder systems are characterized by the assemblage of several economically useful plants of various forms and growth habits ranging from cucurbitaceous vegetables at the edge of a small rice field in the foreground and the family dwellings lined by palm trees, bananas, and a variety of other fruit trees in the high ground behind. (Photo: S Deb)

conventional agricultural systems. In a unique study to determine the influence of agroforestry practices (shaded coffee and homegardens) on biodiversity in an agricultural mosaic, Francesconi et al. (2013) monitored the distribution of the fruit-feeding butterfly in the Pontal region near São Paulo, Brazil. Given that butterflies are considered sensitive to variations in the environment, their presence in the different land-use practices in the agricultural landscape was considered an indicator of habitat preference. Overall, shaded coffee practices that represent long-term mixed tree and crop stands were found to have a better potential of conserving forest butterfly species compared to monoculture practices of eucalyptus (*Eucalyptus* spp.), cassava (*Manihot esculenta*), and sugarcane (*Saccharum officinarum*).

More than 90 % of the biodiversity resources on Earth are found in human-dominated tropical landscapes (Garrity 2004). Concerns have been raised, however, that the landscape-simplification process occurring across many tropical and subtropical countries could be a major threat to agrobiodiversity, as mentioned in Section 21.4. Nevertheless, a recent meta-analysis (Beckmann et al. 2019) illustrated that small-scale land-use intensification steps characteristic of low-intensity systems such as agroforestry may not adversely affect yield or species richness profoundly. Although species distinctiveness (presence of rare or endemic species) of such anthropogenic systems is frequently low, species richness is quite substantial. The overall contribution of agroforestry to biodiversity conservation will depend on the kind of land use that it supplants and on the attributes of the specific agroforestry system established (Swallow and Boffa 2006). The ensuing sections entail a description of how agroforestry enhances species diversity at the farm and landscape levels.

21.6.3 Species Diversity in Agroforestry

Highly complex agroforestry systems such as tropical homegardens with considerable diversity of components are characteristic of the geographic regions with high human population density such as South and Southeast Asia (Chapter 7). Botanical surveys of the homegardens of southwestern Bangladesh revealed 419 species including six that were on the IUCN Red List for Bangladesh (Kabir and Webb 2008). In parts of Latin America and West Africa, coffee and cacao (both shade-tolerant crops: Chapter 8) are traditionally cultivated under an open canopy of remnant trees that are retained when a forest is cleared, resulting in the formation of another type of complex agroforests (Schroth et al. 2004). Tree diversity abounds in all such systems, and some of the tree species in those agroforests can also be found in the adjoining forests.

Genetic Diversity: Yet another dimension of species diversity is genetic (intra-specific) variation among crop and tree populations. Many landraces of crop plants and genetically diverse tree populations occur in agroforestry systems. For instance, nearly 10,000 varieties of apples and 1000 to 2000 varieties of plums are maintained *in situ* in *Streuobst,* a traditional agroforestry system in temperate Europe (*c.f.* Vallejo-Ramos et al. 2016; see also Chapter 9). Likewise, several cultivars of fruit trees are conserved in the tropical homegardens (Kumar and Nair 2004). However, the genetic diversity of agroforestry trees has not received much scientific attention in the past; yet some aspects relating to domestication of fruit trees were focused (e.g., Akinnifesi et al. 2008; Clement et al. 2015). In one of the reviews on biodiversity attributes of agroforestry, Dawson et al. (2013) stated that semi-domesticated tree species in agroforestry systems frequently maintain high levels of intra-specific diversity. Hence promoting tree domestication beyond a threshold may have negative implications on the diversity of agricultural landscapes at both inter- and intra-specific levels as can be seen in the case of clonal tree monocultures. But without improvements in tree productivity and quality associated with domestication, farmers are also unlikely to plant trees on their land (Sunderland 2011), implying a trade-off between intraspecific diversity and tree productivity.

Soil Biota: Apart from augmenting aboveground biodiversity, trees in agricultural landscapes also can enhance belowground biodiversity. The greater soil biodiversity in agroforestry compared to monoculture crop systems can be explained based on factors such as shading and the associated microclimate buffering and the continuous supply of organic matter inputs into the rhizosphere (Chapter 16). The soil biota falls under four broad functional groups: (1) decomposers, (2) nutrient transformers, (3) ecosystem engineers, and (4) biocontrollers. The corresponding ecosystem functions they perform are carbon transformations, nutrient cycling, soil structure maintenance, and population regulation (density-dependent mechanisms), respectively, which together sustain soil health (Kibblewhite et al. 2008; Wall et al. 2012; Wall and Knox 2014; Barrios et al. 2018). While it is presumed that activities of all these categories of organisms will be stimulated by the presence of trees, quantitative information on the relative abundance of different groups of biota is not available.

A robust relationship between aboveground biodiversity and belowground biodiversity also has been reported by many (e.g., Wardle et al. 2004; Barrios et al. 2018; Villanueva-López et al. 2019). Wardle et al. (2004) argued that “aboveground and belowground communities can be powerful mutual drivers, with both positive and negative feedback”. Consistent with this, Rahman et al. (2012) showed that increasing tree cover in agricultural landscapes supported higher soil invertebrate biodiversity compared to tree-less or reduced tree-cover landscapes and significantly improved the ecosystem functions that underpin ecosystem services. Likewise, Villanueva-López et al. (2019) found a significant positive correlation between macro-arthropod diversity and plant species richness in traditional agroforestry systems in the humid tropics of Mexico. Tree cover management and aboveground biodiversity thus can affect soil biota and the provision of soil-based ecosystem services in agricultural landscapes.

Wild Biodiversity: Refers to the diversity of forest plants, animals, and microorganisms. McNeely and Schroth (2006) argued that agroforestry practices may enhance levels of wild biodiversity on farmlands, and support conservation of biodiversity in remnants of natural habitats that are interspersed with farmlands in tropical land-use mosaics. This is because the integration of trees into multiple-use landscape matrices improves landscape connectivity and maintains heterogeneity and complexity of the vegetation structure. In another study in the Andes Mountains of Venezuela, Bakermans et al. (2012) found that the density of neotropical migratory birds increased with the structural complexity of shaded coffee farms, denoting a significant effect of structural and floristic attributes on migratory bird density.

The bottom-line is that agroforestry practices, especially those in the tropics, are biodiversity-friendly ways of agriculture and are a potentially valuable conservation tool that can be useful for easing land-use pressure while enhancing rural livelihoods (Garrity 2004). A meta-analysis of 53 publications on European agroforestry systems revealed an overall positive effect of agroforestry on biodiversity conservation and ecosystem services over conventional agriculture and forestry (Torralba et al. 2016) in the temperate regions as well. However, conservation goals may generally conflict with production imperatives (Waldron et al. 2012), and the landscape-level simplification process aimed to maximize productivity may have potentially negative implications for biodiversity and ecosystem services. Creating and maintaining agroforestry habitats in human-dominated landscapes should, nonetheless, be part of a comprehensive biodiversity conservation strategy.

21.6.4 Habitat Diversity: Some Empirical Aspects

One of the principal drivers of farmland biodiversity is landscape heterogeneity, which is generally high in the traditional land-use systems. Ecosystems worldwide, however, are encountering human-induced habitat homogenization. Agricultural landscapes with relatively high agroforestry cover represent intermediary levels of habitat diversity between the natural (forest) ecosystem and single-species agricultural production system (Figure 21.3). Reviewing the literature on

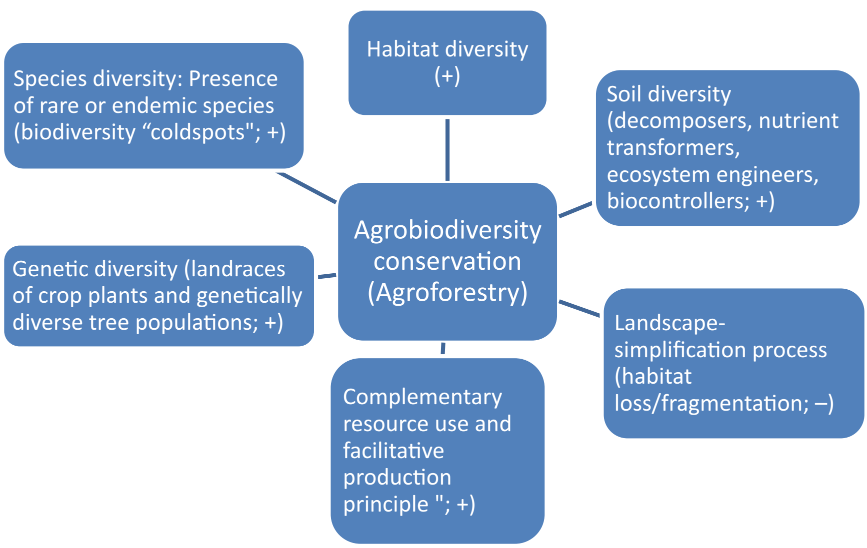

Figure 21.3 Conceptual diagram showing various components of agrobiodiversity and their linkages to agroforestry; + and – signs indicate positive and negative effects on agrobiodiversity conservation respectively. The boxes representing positive features (+ signs) are intrinsic features of agroforestry; while landscape simplification (– sign) is a function of landuse management

agroforestry and biodiversity, Schroth et al. (2004) proposed three hypotheses to explain the functional roles of agroforestry in biodiversity conservation on a landscape scale:

- The *Agroforestry-Habitat Hypothesis,* providing supplementary, secondary habitat for species that tolerate a certain level of disturbance, signifying the role of agroforestry systems for maintaining heterogeneity at the habitat and landscape scales (e.g., agroforestry systems such as tropical homegardens harbor some forest-dependent plant and animal species, besides acting as reservoirs of the tree- and crop germplasm; see also Sections 21.6.3, 21.6.6, and Chapter 7);
- The *Agroforestry-Deforestation Hypothesis*, implying the reduction of rates of conversion of natural habitat by providing an alternate source for such products so that the pressure on forest reserves is eased;
- *Agroforestry-Matrix Hypothesis,* creating a more benign and permeable 'matrix' between habitat remnants (compared with less tree-dominated landscapes), which support the integrity of these remnants and the conservation of their populations; for example, strategically placed agroforestry systems may serve as biological corridors between patches of natural vegetation or act as stepping stones that facilitate animal movement. Shaded production systems such as cacao and coffee agroforestry are excellent examples of this, and they improve the quality of the landscape matrix and can play an important role as a buffer zone around protected areas and forest patches (Valencia et al. 2014).

21.6.5 Pathways for Conservation of Tree Diversity in Smallholder Agroforestry Systems

Dawson et al. (2013) proposed three pathways for conserving tropical trees through smallholder agroforests.

- ***In situ* conservation** refers to the maintenance of tree diversity essentially in the wild forest and woodland populations, and aligns roughly with the Agroforestry-Deforestation Hypothesis mentioned above. To reduce extraction from the forest and facilitate conservation, alternative sources of tree products are provided by cultivating trees in smallholdings around natural forests and woodlands or as "corridors" or "stepping stones" that link fragmented wild stands. Although this strategy is widely promoted as an effective conservation strategy, only anecdotal evidences are available to support the effectiveness of this approach (Paquette and Messier 2010).
- ***Ex-situ* conservation** refers to the preservation of trees in seed banks, seed stands, botanical gardens, and field trials, or maintaining them in other "exotic" locations outside the usual environments, systems, and/or geographic settings of the species. Planting trees in managed ecosystems may generate greater interest in including them in seed collections, field trials, and field genebanks, but their conservation value *per se* is limited; moreover, the scientific, technical, and resource limitations constrain *ex-situ* programs (National Research Council 1991).
- ***Circa situm* reservoir of biodiversity** refers to the preservation of planted and/or relic trees and wildings in farmland where natural forest or woodland containing the same trees existed once but has been lost or altered significantly through agricultural expansion. For example, Hughes (1998) attributes the relative abundance of a wide range of *Leucaena* species in Mesoamerica, despite the loss of forest cover in most areas, to their management for several centuries by local communities and farmers in various ways and for various products and services. With the limitations of both the *in-situ* and *ex-situ* approaches to conservation, such farmer-based conservation has been used to distinguish the different circumstances of conservation within altered agricultural landscapes (e.g., homegardens and other agroforestry systems) outside natural habitats but within a species' native geographical range. This aligns roughly with the Agroforestry-Habitat and Agroforestry-Matrix hypothesis mentioned above (Section 21.6.4). Given the contemporary global challenges to

biodiversity, there is a need to rely increasingly on a *circa situm* smallholder-farm approach, i.e., transitioning to lower and less valuable (from a conservation perspective) farmland tree species diversity over time (Dawson et al. 2013). Several studies have highlighted the increased abundance of mammals, birds, and insects in coffee and other agroforestry systems than in annual and mono-crop systems (e.g., Pinard et al. 2014; Francesconi et al. 2013, 2014), implying the relevance of the *circa situm* approach to biodiversity conservation.

21.6.6 *Land Sharing* Strategy for Biodiversity Conservation in Agricultural Landscapes

The *land-sharing* strategy refers to the integration of agriculture and conservation within multifunctional landscapes of traditional smallholder agroforestry systems, as opposed to the *land-sparing* approach that separates the landscapes into two or more "monofunctional" units optimized for agricultural production and biodiversity conservation (Figures 21.1 and 21.2). Land-sharing is perceived as conducive to the conservation of biological resources *circa situm*. It represents "farming practices that preserve or promote biodiversity within agricultural areas, often using low levels of inputs and minimal disturbance albeit lower yields and therefore a greater area requirement for equivalent production" (Bhagwat et al. 2008). The favorable effects of agroforestry systems on biodiversity conservation are attributed to the greater number of species within limited areas of the agricultural landscape (Figure 21.3). Farmers also have a habit of retaining valuable tree species, which act as islands or refuges for many species (Tolera et al. 2008). Thus, the farmlands provide a habitat for many tree species. Overall, agroforestry produces biodiversity benefits that are intermediate between crop monocultures and primary forests and may help to identify threatened species and their habitats for formulating conservation action.

The long-term conservation values of agroforests, however, have been questioned (e.g., Dawson et al. 2013). Managed agroforests are sometimes more "speciose" at the plot scale than secondary forests, but the species spectrum is different among land-use types (Valencia et al. 2014; Sistla et al. 2016). The preponderance of early successional species and the increasingly infrequent occurrence of late-successional species, and a higher proportion of exotics in certain land-use systems, are major concerns in this regard. A meta-analysis of studies on biodiversity and ecosystem service benefits of coffee and cacao agroforestry based on 74 published papers from across Africa, Latin America, and Asia by De Beenhouwer et al. (2013) found that conversion of natural forest to coffee and cacao agroforest had an overall detrimental impact on total species richness (Hedges' $g = -0.49$). But the intensification of agroforest toward plantation resulted in a much stronger decrease in total species richness (Hedges' $g = -1.26$) than the conversion of natural forest into agroforest. The deliberate choice of species for human consumption is a characteristic feature of agroforestry, which can potentially reduce species diversity (see Section 21.4). Thus, agroforestry systems may not always preserve the rare and endemic forest species, but they can promote the conservation of many other species.

It follows from the above that although networks of protected areas in the tropics provide the best habitat for many rare and endemic species that prefer old-growth forests, these networks are insufficient to protect all tropical biodiversity, and therefore agroforestry could be an important conservation option. Needless to emphasize that the effectiveness of agroforestry in biodiversity conservation depends on the design of the system and the nature of the biodiversity to be conserved. Key design features compatible with conservation goals include high structural and floristic diversity (e.g., multiple species and vegetative strata) and low management intensities. Agroforestry, however, is not a stand-alone approach to conservation; it needs to be seen as one of the components of the conservation strategies

(Swallow and Boffa 2006). As part of a multifunctional working landscape, nevertheless, agroforestry plays a major role in conserving and even enhancing biodiversity from farms to the landscape level in both tropical and temperate regions of the world.

21.7 Ecosystem Resilience

Ecological resilience is frequently defined as the time required for a system to return to equilibrium or steady-state following a perturbation or disturbance (Ives 1995; Johnson et al. 1999). It represents "the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures" (Gunderson 2000). These self-organized processes and structures are the alternative stable states of ecosystems. Broadly, the concept of ecological resilience encompasses two separate processes: *resistance* or "the magnitude of disturbance that causes a change in structure" and *recovery* or "the speed of return to the original structure" (Côté and Darling 2010). An opposing attribute of resilience is *vulnerability*, which is a multidimensional concept. MA (2005) defined vulnerability as the "exposure to contingencies and stress, and the difficulty in coping with them". It signifies the reduced ability of people and landscapes to cope with variability (both natural as well as anthropogenic) and adapt to change (e.g., climate change manifestations such as floods and droughts).

Diversity-stability theory: The relationship between biological diversity and ecological stability has been a focal theme of discussion for long (e.g., May 1973; Tilman and Downing 1994; Tilman et al. 1996; Gunderson and Pritchard 2002). The *diversity-stability theory*, originally proposed by MacArthur (1955), implies that an increase in species number in a plant community increases the efficiency and stability of ecosystem processes if species differ in their environmental responses (Tilman and Downing 1994; Tilman et al. 1996; Ives and Carpenter 2007). However, as the number of species in the community increases, the average population size of the species in the community may decline.

One of the encouraging features of agroforestry, compared to conventional agriculture, is the associated greater belowground and aboveground biodiversity (e.g., N_2-fixing organisms, pollinators, and biological control agents), which favor resilience. Besides, the crop/animal production practices foster greater functional diversity and augment the potential for multiple benefits (multifunctionality). Many argue that food security, health care, and ecosystem resilience of indigenous communities are strongly rooted in the maintenance of biodiversity (e.g., McNeely Schroth 2006; Bhagwat et al. 2008; Bucheli and Bokelmann 2017; Bentrup et al. 2018). For example, the biodiverse homegardens in Central America and Nepal, apart from providing the provisioning ecosystem services, *inter alia*, facilitated the target families to significantly increase year-round production and consumption of vitamin-rich fruits and vegetables (compared to the control group without gardens), thus alleviating deficiencies of iodine, vitamin A and iron (Molina et al. 1993) and made children of garden owners less prone to xerophthalmia (Shankar et al. 1998). Although most studies on aspects relating to the biodiversity of agroforestry systems are reported from the tropics, the numbers of studies reported from the temperate region have increased since 2000 (Udawatta et al. 2019).

Trade-offs: Although agricultural practices that foster enhanced functional diversity increase the potential for multiple benefits, the interactions among multiple ecosystem services for greater resilience are complex and need to be understood more clearly (Barrios et al. 2018). Hoang et al. (2014) argued that despite the multiple values, the complexity of designing and managing agroforestry practices and lower outputs from agroforestry components makes it less attractive compared to intensive monocultures, implying some kind of trade-offs between market-oriented farming and economic and ecological resilience. The paradigm of *Sustainable Intensification* (SI) that has been promoted as a major initiative during the early 2000s could provide some solutions to this production-conservation conundrum.

Agroforestry systems such as homegardens are an integral component of the SI strategy that focuses on linking development and implementation of multifunctional and biodiverse agroecosystems with increasing the yield output per unit of land while improving both environmental and social (livelihood) conditions (Pretty 1997; Godfray et al. 2010; Bommarco et al. 2013).

21.8 Concluding Remarks

One of the overarching themes of agroecological research has been to conserve biodiversity in the managed landscapes (agrobiodiversity). Agroforestry systems play a unique role in this respect. Genetic resources including the species used for food, fodder, fiber, fuel, and pharmaceuticals, and the multiplicity of non-harvested species that sustain production (e.g., soil microbes, predators, pollinators) abound in agroforestry. Such landscapes also epitomize intermediary levels of habitat diversity. Figure 21.3 summarizes the major components of agrobiodiversity and their links with agroforestry. Many indexes are often used by agroforesters and ecologists to characterize biodiversity in agroecosystems.

Agricultural landscapes, where agroforestry is substantial, are presumably the most effective way for conserving biodiversity in managed ecosystems. Such landscapes are often labeled as biodiversity "coldspots" and involve a dynamic mosaic of tree-dominated and crop-dominated patches. They also provide a range of ecosystem services and contribute to more resilient rural livelihoods – owing to the relatively high biodiversity compared to monocultural production systems. Many argue that agroforestry systems especially the smallholders' agroforests may help conserve tropical trees through three main mechanisms, viz., *circa situm* reservoirs of biodiversity, *in situ* conservation by providing an alternative source of products to reduce extraction from forests, and *ex situ* conservation activities. Much of the species diversity in agroecosystems, however, is being eroded owing to widespread intensification and simplification of the traditional land-use systems and landscapes. Although agroforestry systems have considerable potential for biodiversity conservation, the predominance of early successional species, the increasingly infrequent occurrence of late-successional species, and a higher proportion of exotics in certain land-use systems may not augur well with the conservation of species/genetic diversity. Thus, agroforestry, and for that matter, any single approach to land-use cannot be regarded as a stand-alone strategy for conservation; conservation ought to be accepted as one of the components of a multifunctional working landscape with the potential to play a significant role in conserving and even enhancing biodiversity from farms to the landscape level.

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Other Ecosystem Services of Agroforestry

22

Contents

Abstract

This chapter discusses the significant role agroforestry systems (AFS) play in realizing ecosystem services other than soil productivity improvement, climate change mitigation, and biodiversity conservation. Such "other" services include the improvement of hydrological characteristics and water quality, socio-cultural and recreational services, and facilitation for the development of biodiversity hotspots and ecotourism. The tree–crop interaction effects of AFS that can influence the hydrological processes include improvement of soil water storage through enhanced infiltration rates and reduced runoff losses and increase in biomass productivity per unit of water used. The positive role of agroforestry practices such as the establishment of riparian buffer strips in ameliorating the non-point source pollution of water bodies especially in commercial agricultural systems has been well demonstrated. Results of meta-analyses linking ecosystem services of agroforestry practices to overall soil health are also becoming available to show that agroforestry, compared with crop monocultures, provides higher levels of soil-related ecosystem services. Cultural ecosystem services include the non-material (non-monetary) benefits that ecosystems provide to humans, such as spiritual enrichment, intellectual development, and societal and community benefits including recreational, cultural, and aesthetic values. The homegardens are well known for the array of

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cultural ecosystem services they provide in many indigenous societies. Plant health issues, including the whole array of pests, diseases, and weeds, are one of the relatively under-investigated aspects of ecosystem services of AFS. Contrary to “over-tourism” that harms communities by overuse and destruction of resources through overcrowding and commercialization, well-planned ecotourism and ecodevelopment operations centered around agroforestry have excellent potential for economic gains and promoting ecosystem health.

22.1 Introduction

As discussed in Chapter 19, ecosystem services are *the benefits that people obtain from ecosystems*. Ecosystem services as applied to agroforestry refer to a wide variety of services that contribute to an environment that enables and supports the sustainable production of goods and materials of economic, social, and ecological significance to humans. Chapter 19 also recognized the major ecosystem services of agroforestry and outlined the chapter layout for discussing each of them individually: Chapter 20 for carbon sequestration and climate change mitigation aspects, and Chapter 21 for biodiversity conservation aspects of agroforestry. The soil-related issues covered in Section IV of the book (Chapters 15 to 18) such as soil organic matter dynamics and soil fertility management (Chapter 16), biological nitrogen fixation (Chapter 17), and soil conservation and control of land degradation (Chapter 18) are also quite relevant to the broad concept of ecosystem services. Besides, agroforestry systems have significant roles to play in realizing several other recognized ecosystem services such as manipulation of hydrological characteristics and water quality, and cultural and recreational services including opportunities for the development of biodiversity hotspots and ecotourism. This chapter will discuss the role of agroforestry in realizing the prominent among these “other” ecosystem services. Perceiving that the ecosystem refers to *the organisms and the non-living environment with which they interact* (Chapter 19), the broader issue of food security can be considered as reflecting the interplay of all of the above ecosystem services, and that topic will be considered as a separate chapter (Chapter 23).

22.2 Hydrological Characteristics and Soil Water Storage

Integrating trees into the production systems could have two major effects on hydrological processes affecting water storage and availability in the system: 1. Improving soil water storage through enhanced infiltration rates and reduced runoff losses, and 2. Improving water quality and reducing pollution of water bodies. Some other effects are more indirect than direct results of tree integration and are often categorized as the tree–crop interaction effects (competitive, complementary, or supplementary) as discussed in Chapter 14. For example, competition for soil moisture between the tree and the arable crop components under water-limited environments is a major issue related to water – and hence hydrological characteristics. Being a form of competitive interaction, however, it may be considered an ecosystem “disservice” rather than a service. Such semantic opinions need not be taken too seriously in agroforestry, which itself was considered by some as a semantically incorrect term in the beginning (Chapter 1). Additionally, in waterlogged soils of salt-affected lands in arid and semiarid regions, there could be the so-called biodrainage effect, which, although a beneficial interaction and an ecosystem service, is still at a conceptual stage with insufficient research evidence to support it, as discussed in Chapter 18, Section 18.8.

Soil Water Storage and Availability. Increasing soil water infiltration rates and reducing runoff losses are two major, interrelated strategies for increasing soil water availability. Enhanced infiltration rates increase soil water storage and decrease the residual quantity of precipitation available for runoff or as the overland flow that happens when the water fails to infiltrate into the soil. In many situations, tree-based production systems may hold considerable promise for both, subject to local conditions. Field research on this aspect has been limited; however, available results support the assumption. In a multi-species riparian buffer in the Midwestern USA, Bharati et al. (2002) noted a five-fold higher soil infiltration rate compared to grazed and cultivated fields. Seobi et al. (2005) reported higher saturated hydraulic conductivity (a measure of the ability of the fluid, e.g., water, to pass through a medium) in a field planted with grass + tree buffer strips (4.5 m wide and 36.5 m apart) compared with row crops in the claypan soils in northeastern Missouri, USA; the grasses included redtop (*Agrostis gigantea),* brome (*Bromus* spp.), and birdsfoot trefoil (*Lotus corniculatus)*, and the trees included pin oak (*Quercus palustris*), swamp white oak (*Q. bicolor*), and bur oak (*Q. macrocarpa*), at 3-m intervals in the center. Wang et al. (2015) found from an 11-year study in the Loess Plateau of China that walnut (*Juglans regia*) + wheat (*Triticum aestivum*) alley cropping system had a significantly higher constant infiltration rate than in the monoculture systems (Figure 22.1). The infiltration capacity of the soil under the alley cropping improved steadily with time as the age of the alley cropping system increased, which the authors attributed to the cumulative beneficial effect of tree roots on soil physicochemical properties. Sediment trapping is another beneficial effect of agroforestry on sloping lands (see Chapter 18, Section 18.5.5). The tree roots and trunks act as permeable barriers to reduce sediment and debris loading into rivers following floods through sediment trapping and runoff reduction. This, to some degree, can abate the risk of flash flooding and the potential for soil erosion following periods of heavy rainfall. For example, Benavides et al. (2009) reported from New Zealand that widely spaced poplars (*Populus* spp.) reduced landslide-induced losses in pasture production following a cyclonic storm by 13.8%, and, on average, each tree protected an area of 8.4 m^2 from damage.

Results of meta-analyses linking ecosystem services of agroforestry practices to overall soil health are also becoming available; for example, two recent (2019 and 2020) such analyses were reported in Chapter 18 (Section 18.5.5). In one of

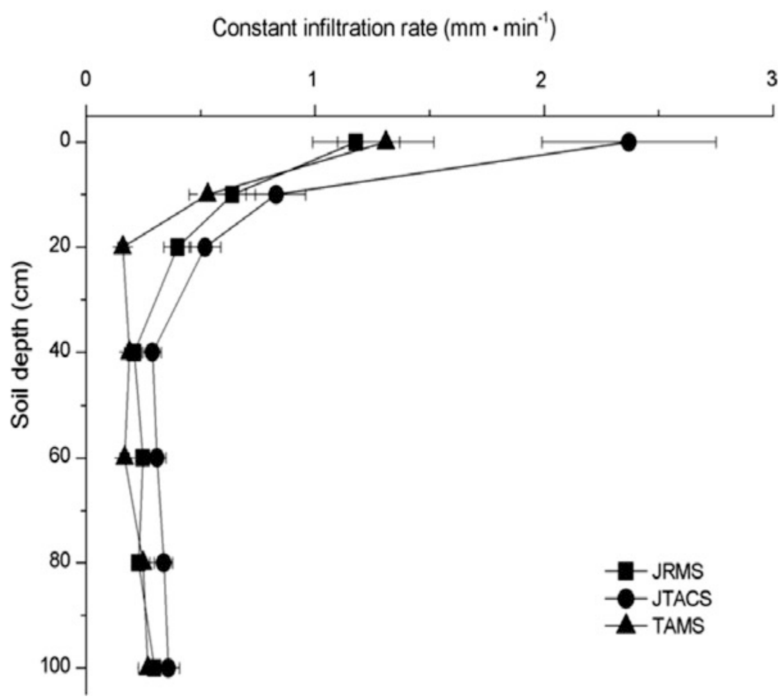

Figure 22.1 Variation of the infiltration rate as the soil depth increased for three land-use systems: walnut (*Juglans regia*) monoculture system (JRMS), wheat (*Triticum aestivum*) monoculture system (TAMS), and walnut-wheat alley cropping system (JTACS) in the Loess Plateau of China. Adapted from Wang et al. (2015)

them based on published studies from semiarid sub-Saharan Africa, Kuyah et al. (2016) noted that agroforestry practices reduced runoff and soil loss and improved infiltration rates and soil moisture content. In the other study focused on the humid and subhumid tropics, Muchane et al. (2020) also found that "agroforestry reduced soil erosion rates by 50% and increased infiltration rates compared to crop monocultures." Despite the limitations in both the original studies based on which the meta-analyses were done and the procedures and assumptions used for the meta-analyses, the overall message is that agroforestry, compared with crop monocultures, provides higher levels of soil-related ecosystem services such as erosion control, enhanced infiltration, amelioration of soil acidity, and enhanced soil carbon storage.

Improving Water Productivity. Water productivity or water-use ratio of a crop or tree + crop mixture is usually expressed as total dry matter produced (kg) per unit volume (m^3) of water. Trees grown on farms with crops (agroforestry) are claimed to have the potential for improving water productivity in two ways (Ong and Swallow 2003): 1. by increasing the amount of the water that is used as the tree or crop transpiration, and 2. by increasing the productivity of the water that is used by increasing the biomass of trees or crops produced per unit of water used. The authors noted that although the evidence for the latter was limited, evidence from semiarid regions of India and Kenya showed that the agroforestry systems had higher (water) productivity compared to the monoculture of crops alone and that was primarily due to the higher amount of water used productively (i.e., transpired rather than evaporated, lost as runoff, or drained to below the rooting zone). Almost half of the total water use occurred during the dry season when cropping was impossible. This implies a high temporal complementarity between the crop and tree components of the landscape mosaic (Ong et al. 2000, Ong et al. 2002). On the other hand, a different type of spatial complementarity in water use has been observed between components of the shaded perennial agroforestry systems. Muñoz-Villers et al. (2020) studying the soil-water use pattern in a coffee (*Coffea arabica*) under shade trees (*Lonchocarpus guatemalensis*, *Inga vera,* and *Trema micrantha*) in Veracruz, Mexico, reported that during the wet season coffee plants substantially increased the use of near-surface water (+ 56% from < 5 cm depth), while shade trees extended the water acquisition to much shallower soil layers (+ 19% from < 15 cm depth) in comparison to drier periods. However, more variability in plant water sources was observed among species in the rainy season when water stress was largely absent, and a greater soil water partitioning prevailed among tree and coffee species when higher soil moisture conditions were present. Despite such variability in plant–soil water interactions across seasons, however, a clear spatial segregation of the main water source prevailed between shade trees and coffee plants during the rainy and dry periods.

Overall, the soil-related beneficial effects of ecosystem services of agroforestry could be attributed to several factors, especially improvement in soil organic matter and consequent improvement in soil physical properties as discussed in Chapter 16. An increase in the proportion of dead roots and root channels and consequently macropores formed following root decay could result in higher soil water flow rates (Rachman et al. 2005; Udawatta and Anderson 2008). Tree canopies may also intercept some precipitation and reduce the amount reaching the soil surface and lower the runoff potential. On the other hand, soil compaction and degradation caused by overgrazing by animals leading to accelerated soil erosion during the rainy season is a serious problem in many grazing systems, especially in the uncontrolled and extensive pastoral and silvopastoral systems of the tropics (Chapter 9, Section 9.4). The extent to which such results are broadly applicable is not clear, however, and convincingly adequate research results of this nature are not available, nor have the modeling efforts that have only been rather limited, produced any significant widely applicable results.

22.3 Water Quality Enhancement

Contamination of water bodies (surface- and groundwater) is a major environmental concern globally today (Figures 22.2, 22.3, and 22.4). According to a UNEP report, pollution of rivers and other water bodies has been aggravated since the 1990s in many countries, and intensification and expansion of agriculture is one of the major causal factors of this grave problem (UNEP

Figure 22.2 Contamination of Chao Phraya River Basin, Thailand from domestic, agricultural, and industrial discharges. Reproduced from UNEP (2016). (Photo: Pinida Leelapanang)

Figure 22.3 Several of the major water bodies and swamps of Florida, USA, are seriously impacted by the luxurious growth of cyanobacteria that seriously threatens tourism and ecosystem integrity. (Stock photo: Jaimie Tuchman, with permission)

Figure 22.4 Another major effect of water pollution on Florida's coasts is the largescale death of fish and other aquatic animals and its impact on tourism and quality of life. (Stock photo: Jillian Cain Photography, with permission)

2016). Loading up the aquatic systems with nutrients and other chemicals from fertilizers and the wide spectrum of agrochemicals used in intensified chemical agriculture causes the build-up of such pollutants at points away from the points where they are originally applied, resulting in the so-called **non-point source pollution (NPSP).** Caused frequently by discharges from feedlots and cropped areas, NPSP is a serious environmental problem, especially in industrialized countries, leading to altered water chemistry with eutrophication (dense growth of plant life and death of animal life in a lake or other body of water, due to excessive richness of nutrients resulting from runoff from the land) and food web modifications (Lemley and Adams 2019).

The establishment of VBS (vegetative buffer strips), discussed in Chapter 10 (Section 10.3.4) and Chapter 18 (Section 18.4.4), and riparian land/water buffer zones are widely recognized strategies to offset the adverse impacts of nutrient transport from the landscapes to freshwater ecosystems. These VBS barriers are linear strips of permanent vegetation including herbs, grasses, shrubs, or trees separating arable land from watercourses or Figures 10.6, 10.7; and Figure 18.4). By trapping and removing various nonpoint source pollutants from both overland and shallow subsurface flow pathways, the barriers facilitate the maintenance or improvement of water quality (Dosskey et al. 2010; Parn et al. 2012). The processes by which multi-species riparian VBS reduce or mitigate the export of agrochemicals include both direct ion-uptake by plants and microbes and indirect influences such as the supply of organic matter to soils and channels, changes in water flows, and reduced rates of soil erosion.

Buffer strips including trees and shrubs are effective strategies to abate sediment transport too. Although phosphorus (P) concentration in the soil solution is mostly low, the P loading of water bodies due to the transportation of P sorbed colloidal particles by surface runoff and soil erosion is a major risk for surface water quality.

Therefore, reducing the transport of sediment-bound (sorbed) P is critical for downstream lakes where this P can desorb and produce extended eutrophic conditions (Nair et al. 2007). Several studies have demonstrated that riparian buffers effectively reduce P loading of streams from croplands by restricting P movement through overland flow (Roberts et al. 2012; Mander et al. 2017). As P accrues in riparian buffer sediments, the capacity of the buffer for P pollution abatement decreases with time unless a management strategy, such as removing plant material that has accumulated P, is adopted (Dodd and Sharpley 2015). Although a considerable amount of P can be deposited in sediments, these sediments may be re-suspended during subsequent hydrological processes, and as discussed above, the P sorbed onto the sediment particles may be desorbed. Borin et al. (2010), based on previous studies, stated that VBS reduced 70 to 90% of suspended solids and 60 to 98% of P. Udawatta et al. (2011) found that agroforestry buffers in the Midwestern United States reduced sediment transport and total P losses by 32 and 46% respectively compared with control treatments. Based on a literature review on the effect of agroforestry practices on reducing surface runoff, soil erosion, and soil nutrients and pollutants, Zhu et al. (2020) reported that on average, agroforestry systems reduced surface runoff, soil, soil organic carbon, and related nutrient losses by 1–100%, 0–97%, –175–92%, and –265–100%, respectively, with average values of 58%, 65%, 9%, and 50%. The herbicide, pesticide, and other pollutant losses were reduced by –55–100% (49% on average). The authors emphasized, however, that the efficiency of agroforestry systems would be site-dependent, varying widely depending on different biophysical factors.

In addition to ameliorating nutrient export, agroforestry systems are reported to have the potential to mitigate the movement of harmful bacteria such as *Escherichia coli* into water sources (Dougherty et al. 2009) and reduce the transport of veterinary antibiotics from manure-treated agroecosystems to surface water resources (Chu et al. 2010). Lin et al. (2011) found that the VBS reduced the transport of both dissolved and sediment-bound herbicides and veterinary antibiotics in surface runoff by 58 to 72%, and VBS of tall fescue (*Festuca arundinacea*) was the most effective in the claypan region in the Midwestern United States.

The safety-net concept surrounding tree roots (Chapter 16, Section 16.5.3; Chapter 14, Section 14.3.2) could have an important application in the heavily fertilized sandy soils that have low nutrient retention capacities (Nair and Graetz 2004; Nair et al. 2007). The capacity of tree roots to capture nutrients from the deeper soil horizons can enhance nutrient storage in the plant-soil system and therefore reduce the mass of nutrients that might otherwise be transported to ground and surface water through runoff and leaching and thus cause NPSP of these water bodies. Considering the extensive rooting pattern of pine trees (*Pinus* spp.), this could be particularly important in the case of pine-based systems such as silvopastoral systems, which is the most common form of agroforestry in subtropical Florida and other parts of southeastern United States (Chapter 10, Section 10.3.2). Michel et al. (2007) studying soil P loss from silvopastoral systems involving slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) and treeless pastures systems in the Spodosols and Ultisols in northern Florida found that P buildup within the soil profile and therefore the chances for loss of P from soil to water bodies were less from silvopastures than from treeless pastures (Figure 22.5). From another study on a Spodosol in Central Florida, Nair et al. (2007) reported that soil P concentrations down to 1 m-depth were higher in a treeless pasture of bahiagrass than in a silvopasture of bahiagrass under 20-year-old slash pine trees and a pasture of native silvopasture vegetation under pine trees (Figure 22.6). They attributed the lower P concentration in the silvopasture to more extensive rooting zones and higher nutrient uptake in the silvopasture combination of tree + forage. These

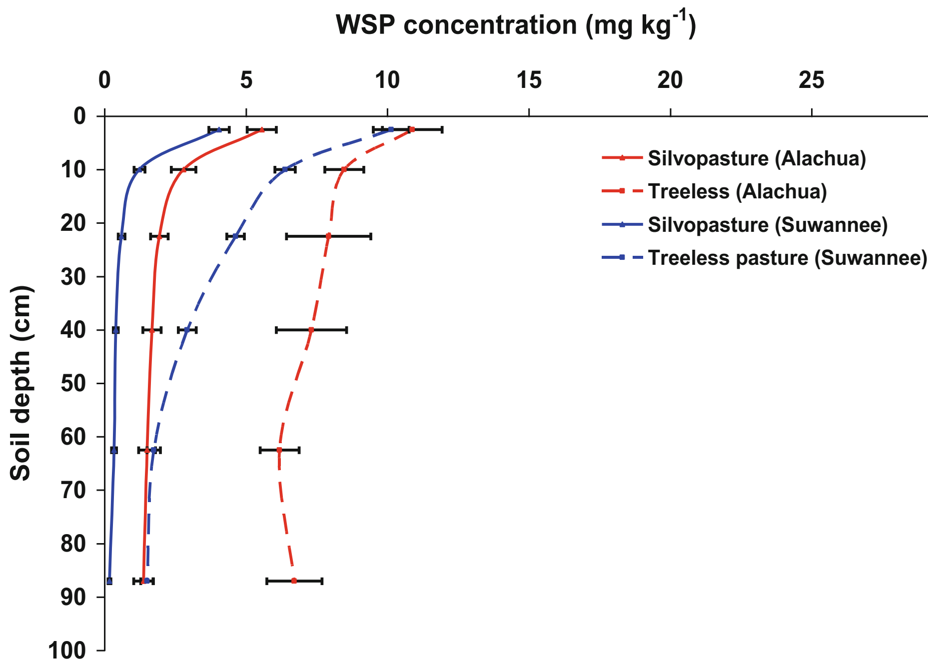

Figure 22.5 Water-soluble P concentrations by depth in silvopasture and treeless pasture systems in Florida Source: Michel et al. (2007)

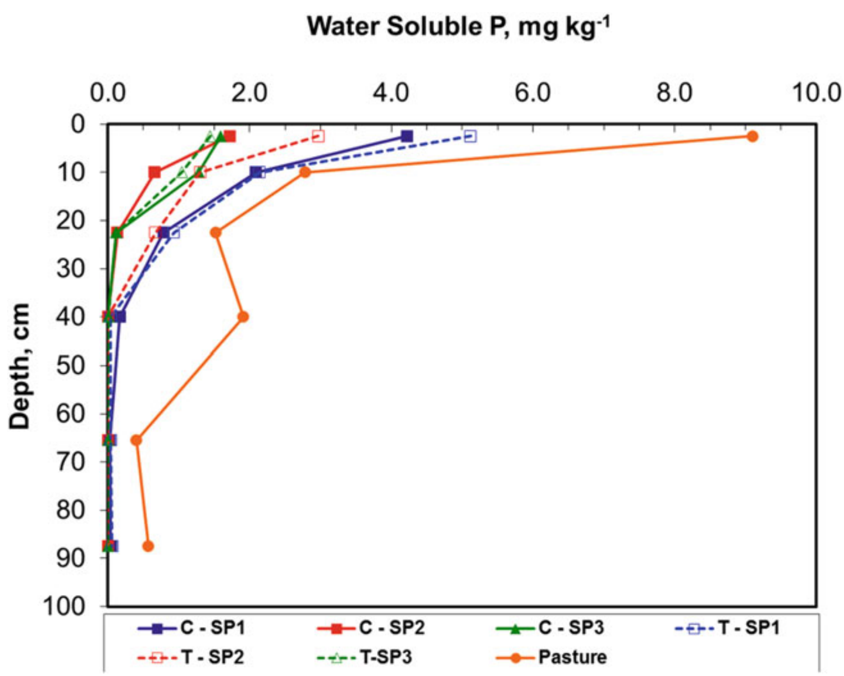

Figure 22.6 Changes in water soluble P (WSP) with depth at three silvopastoral locations, SP1, SP2, and SP3, and at a treeless pasture (Pasture). At the silvopastures, the changes in WSP are shown within soil profiles from the center of the alley (C) and in-between the tree rows (T). Depth indicated is the mid-point of the sampled depth (Source: Nair et al. 2007)

results are, however, only indicative, and more results from a wide variety of ecosystems are needed to arrive at widely applicable conclusions.

22.4 Cultural Ecosystem Services (CES)

Cultural ecosystem services include the non-material (non-monetary) benefits that ecosystems provide to humans, such as spiritual enrichment, intellectual development, and societal and community benefits including recreational, cultural, and aesthetic values. This is a broad subject of enormous importance, and the authors of this volume do not consider themselves competent to discuss it in deserving detail. Nevertheless, a few observations are included here that might be relevant to any future socio-cultural evaluation of agroforestry systems as a sequel to the outstanding two-volume treatise (Cairns 2007, 2015) of the indigenous knowledge surrounding traditional shifting cultivation in the tropics. The singing and dancing and such other recreational relaxations and sociocultural rituals are associated with many traditional land-management activities in many societies throughout the world especially in low-input systems such as agroforestry. Two examples are included in Figures 22.7 and 22.8. These "services" are not exclusively the services or benefits provided by the agroforestry systems *per se*. Rather, they represent the interplay of various aspects of the way of life of the land users and communities, of which traditional land management is one of several interconnected activities. And therein lies the difficulty in separating and quantifying the value of ecosystem services that can be attributed specifically to agroforestry or other specific forms of land-use management.

Figure 22.7 Sociocultural services of traditional agroforestry systems: The *Chagga* gardens (Chapter 7) have traditional bonding with the socio-cultural habits, lifestyles, and rituals of the local community (near Mt. Kilimanjaro) as in this song-and-dance celebration by the local women. (Photo: BM Kumar)

Figure 22.8 Sociocultural values of agroforestry systems. There is a long tradition of singing and dancing associated with shea butter gathering from the *Vitellaria paradoxa* tree (Chapter 13, Appendix I in Burkina Faso and other parts of the West African Sahelian region. (Photo: P. Lovett)

22.4.1 Traditional Ecological Knowledge

The practitioners of traditional land-use systems such as agroforestry possess a vast store of traditional ecological knowledge (TEK) about their specific landscapes and how best to maintain them in perpetuity. This knowledge-base and traditions acquired and/or developed through repeated trial-and-error procedures, represent the perpetual fine-tuning of information concerning the interactions of plants and their environment as well as interactions between agricultural and social systems. The net effects of these manifest themselves as the wide variety of different management practices ranging from the planting technique involving fruit trees and crops as in the *Streuobst* or Chania system in Europe to the management of *Acacia nilotica* trees in and around the fields of rice and rain-fed crops in India (Chapter 13, Appendix I, Figure 13.A.I.2). The knowledge-base and the unwritten rules binding them are handed down by word of mouth from generation to generation of landowners, such that the reasons and circumstances of why, how, and when these systems started, and what modifications they have gone through are unknown. The longstanding observations and beliefs, which the indigenous farmers inherit, are continuously being modified and enriched through experimentation and adaptation to changing environmental conditions and societal needs over generations as documented elaborately by Cairns (2007, 2015).

In land-use history around the world, several examples are available to show that when large groups of people migrate willingly or due to socio-political reasons from their native regions to far-away places, sometimes in different continents, they take with them their beliefs and cultures, including those related to land husbandry methods to the new habitats. Those beliefs and practices are then modified and adapted to the new surroundings. In agroforestry, several such examples of AFS have been reported; for example, the “Tomé-Açu system” of homegardens in

Tomé-Açu, Pará State, Brazil (Chapter 7, Section 7.7.7). The success story of these Japanese settlers who developed a flourishing and exceptionally productive and integrated AFS have been elaborately studied and the results published in international literature (Yamada and Gholz 2002; Yamada and Osaqui 2006). Interestingly, the settlers who were lacking in personal experience of managing tropical homegardens when they arrived from Japan in the 19th and early 20th century (Yamada and Gholz 2002), used their native intelligence and innovative skills and developed a system adapted to the local conditions, which has since become a shining example of integrated, modern homegarden (Porro et al. 2012). Another interesting example is provided by Westmacott (1992) who describes how African Americans and the rural Caribbean settlers in the southern United States have maintained their traditional sociocultural and the TEK traditions of their forefathers in maintaining their household the gardens and yards. Based on historical research, field observations captured in drawings and photographs, and oral interviews, the author has described the characteristics of the integrated gardening followed by the practitioners, and "how a culture expresses itself, is perpetuated, changed, and integrated."

Natural areas are considered more important in the context of CES, but the "social-ecological interactions in the farming landscapes commonly result in agroecosystems with exceptional cultural benefits" (Hanaček and Rodríguez-Labajos 2018). Connectedness to nature, which is of paramount importance for providing cultural and spiritual fulfillment of people, has been a major attribute of all traditional land-use systems including agroforestry around the world as shown in the Nair et al. (2018) evaluation of the so-called Cinderella agroforestry systems (Chapter 11, Section 11.2). In affluent societies too, most landowners are motivated by a yearning for CES rather than cash income, and people in the temperate countries increasingly use the urban and peri-urban spaces to produce food (Section 10.3.5) for a variety of purposes, an important one being the desire of the urban population to reconnect with nature (Plieninger et al. 2015).

The notion of cultural landscapes, which represent the interface between nature and culture, is also well ingrained in many traditional societies (Berkes et al. 1998). Such landscapes are indeed central for spiritual fulfillment and to comprehend the importance of human and cosmic existence. Throughout the world, at different times in history, cultural landscapes such as sacred forests and groves, sacred corridors, and a variety of ethnoforestry practices that mirror ecosystem-like concepts have evolved. Many of these are also aligned with agroforestry. The protection and management of cultural landscapes have attracted international attention; for example, the acknowledgment of cultural landscapes in the UNESCO World Heritage Convention (Rössler 2006). Another example of a social-ecological system drawing international attention is the *Satoyama* Initiative; a brief account of the satoyama landscapes of Japan which is included in Chapter 11 (Section 11.5.8), and more analytical descriptions are provided by Takeuchi (2010), Ichikawa and Toth (2012), and others.

22.4.2 Ethnoforestry and Tropical Homegardens as Providers of CES

The literature on ethnoforestry is replete with descriptions of religious knowledge that can be useful for eco-restoration and often has ingredients of adaptive management (e.g., Berkes et al. 2000; Bhagwat et al. 2005). Religious beliefs, worshiping the sacred lands, animals, or trees are very popular and represent the traditional way of nature protection for ethnic people (IPBES 2018). In many traditional societies, various plant species are deliberately included – or excluded – from the farm and landscape for their assumed religious or cultural values, medicinal properties, or traditional belief about them as harbingers of prosperity or calamity (see, for example, Chandrashekara et al. 2012, for an assessment of the ecosystem services of the Sacred Groves of Kerala, India). In many societies, "the relationships between the natural environment and health are mediated by locally distinct cultural associations with species or habitats" (IPBES 2018). For example, *Ocimum sanctum*, a medicinally important herb in India locally known as *Tulsi* is worshiped throughout the country. The aromatic, medicinal, and therapeutic values of a whole host of plant species grown in homegardens and other agroforestry systems are legion in several regions and religions of the world (Chandrashekara and Sankar 1998; Rao et al. 2004; Kumar 2008).

A special mention needs to be made about the role of tropical homegardens in this regard (Chapter 7). The choice of plants cultivated in the homegardens strongly reflects the culture of the gardeners practicing it. Terra (1954) and many other subsequent authors (e.g., Kumar and Nair 2004; Mohri et al. 2013) have proposed the notion that intensive homegardening is predominantly associated with matrilineal societies. Planting and maintaining of homegardens also reflect the status of the household, especially women in the local society. In many areas, women play a vital role in the design and management of these land-use systems, including the introduction or reintroduction of species into the homegardens. Kumar and Nair (2004) argue that "the possibility of gender equality for participating in garden management and sharing of benefits is perhaps one of the major stimuli for continued household security enjoyed by homegardeners for generations."

Homegardens also constitute an important recreational resource in many regions of the world. For instance, in the traditional Javanese homegardens, a shaded patch is set aside to be used as a playground for children and as space for elders to "hang around" during their free time. In the Kandyan gardens of Sri Lanka also, such spaces facilitate intra-family interaction, besides providing a place for people to meet, for children to play, and for other occasional social events. Although the traditional Javanese homegardens are normally bordered by a "biofence" of shrubs or small trees, there is hardly any access control system in place for friends and neighbors, who wish to enter the garden for fetching water or gathering medicinal plants, or for other sundry needs. Indeed, homegardens help enhance the community′s social networking and the notion of trespassing is completely alien to Javanese homegardeners. The homegarden produces are also freely shared among relatives and neighbors, "thereby fostering equitability within the community′s social fabric" (Mohri et al. 2013). That used to be the tradition in Kerala homegardens (India) too, but it has changed over the years and the tradition is giving way to the demands and norms of modernization including boundary walls and isolation. Overall, homegardening facilitates increased fulfillment of social and cultural needs through sharing or exchange of produces and recreational opportunities and better preservation of indigenous knowledge. Significantly enough, even expatriate populations from the regions where homegardens traditionally formed the predominant land use activity, practice it widely in their new lands, presumably to "re-invent" their cultural moorings. Mazumdar and Mazumdar (2012) reported that North American immigrants of multiple ethnicities use homegardens as a religious (for meditation and socialization), cultural (ethnic cuisine, ethnomedicine, and identity continuity), ecological (reconnecting people with landscapes left behind as well as forging new linkages to place) and family memorial space for fostering intergenerational connections.

22.5 Plant Health: Control of Pests, Diseases, and Weeds

Plant health issues, including the whole array of pests, diseases, and weeds, are one of the relatively under-investigated aspects of ecosystem services of AFS. Although plant/crop health itself is not a well-defined term (Döring et al. 2012), it is generally used to indicate the "well-being" or the capacity of a given crop to provide ecosystem services, especially regulating and provisioning services such as climate regulation, pollination, pest, weed and disease regulation that are described in Chapter 19.

Insect Pests. Monocultures of crops are widely believed to be vulnerable to the attack of specific pests and, conversely, plant associations are considered as insurance against total devastation by a largescale outbreak of pests and diseases. Indeed, "natural pest control" is touted as a key attribute of agroforestry, and some research results are available to support the beneficial role of agroforestry in this regard (Table 22.1). What contributes to better pest control in agroforestry compared to sole cropping is probably the greater abundance of the natural enemy complexes (predators, parasitoids, and pathogens). Broadly, mixed-species plant associations as in AFS mimic natural or semi-natural conditions and support the proliferation and activities of natural enemies of pests by providing resources such as nectar and pollen, as well as shelters against unfavorable weather conditions (Alignier et al. 2014). In support of this view, several authors have reported higher rates of aphid parasitism, i.e., parasitized aphids (Alignier et al. 2014) and bird predation (e.g., Perfecto et al. 2004; Karp et al. 2013) under semi-natural habitats, compared to monospecific production systems and thus better pest control in the former. A meta-analysis of results of studies of this nature (Pumarino et al. 2015) showed that agroforestry practices resulted in lower pest abundance of perennial crops (e.g., coffee, cacao, and plantain). Earlier studies by Letourneau et al. (2011) and Iverson et al. (2014) also suggested that increasing crop diversity regulated insect pest densities directly or through the action of their natural enemies.

In forestry too, monocultures are widely believed to be vulnerable and susceptible to pest outbreaks (e.g., Lugo 1997). Based on a meta-analysis on more than 50 field experiments that compared pure and mixed-species stands, Jactel et al. (2002) demonstrated a significant increase

Table 22.1 Some examples of pest dynamics and control in agroforestry systems

Crop systems	Pests	Natural enemy complex	Effect	Reference
Shaded coffee (global review)	Coffee berry borer (*Hypothenemus hampei*); *Cercospora coffeicola*, a defoliating fungus	Parasitic wasp *Cephalonomia stephanoideri* and the entomopathogenic fungus *Beauveria bassiana*	Shade trees favored the natural enemies; greater *C. coffeicola* incidence under unshaded conditions	Beer et al. (1998)
Coconut + cacao, Malaysia	Cacao mosquito (*Helopeltis theobromae*)	Predatory ants *Dolicoderus* and *Oecophylla*	Reduced pest damage in mixed plantations; more nest sites for predatory ants	Way and Khoo (1991)
Shaded cacao in West Africa	Mirid bugs and cacao pod borers	More native shade tree species favored higher numbers of wasp nests and spider webs	Lower incidence of mirid bugs and pod borers under shaded plantations	Bisseleua et al. (2013)
Shaded coffee in Uganda	Coffee berry borer	Ants and other hymenopterans (e.g., parasitoids) and birds	Reduced borer population in high-shade systems	Jonsson et al. (2015)
Maize with hedgerows in semiarid Kenya	Stalk borer (*Busseola fusca*) and aphid (*Rhophalosiphum maidis*)	More wasp activity close to hedgerows; 77% higher spider catches during maize season in the presence of hedgerows	Lower infestations than monocrop maize	Girma et al. (2000)
Leucaena leucocephala – maize alley cropping, Kenya	maize stem borers (*Chilopartellus*, *Chilo* sp. and *Sesamia calamistis*)	Lower rates of egg parasitism by *Trichogramma* sp. and *Telenomus* sp. in hedgerow intercropping	Stem damage and plant mortality significantly lower than monocrop	Ogol et al. (1999)
Shaded and open kale (*Brassica oleracea L.*) western Kenya	Aphids, caterpillars	Spiders and predatory beetles	Lower numbers of aphids and caterpillars and more of spiders and predatory beetles in shaded fields.	Guenat et al. (2019)

in insect pest damage in single-tree species forests, and they attributed this to three main factors. First, the existence of physical or chemical barriers provided by other associated plants could reduce the access of herbivores to the large concentration of food resources offered by the high density of host trees in the forest monoculture. Second, the abundance or diversity of natural enemies often observed in mixed-species stands could promote the biological control of insect pests. And third, the potential for a diversion process, i.e., the disruption effect on pest insects resulting from the presence of another more palatable host tree species in the same stand. By extension, such mechanisms may operate in agroforestry too.

The favorable effects of pest suppression in agroforestry are not universal, however. Guenat et al. (2019) found no effect of shade trees on predation and aphid parasitism in agroforestry systems compared to monocultures. Chaplin-Kramer et al. (2011) also reported that though complex landscapes including natural habitat promoted natural enemies, the effects on pests were rather inconsistent. For instance, white stem borers of coffee (*Monochamus leuconotus*) were more common in shaded than in sun-exposed coffee plantations, presumably because of microclimatic changes (Jonsson et al. 2015). However, the opposite trend was noted for coffee berry borer (*Hypothenemus hampei*) incidence (Table 22.1). MacLean et al. (2003) too had suggested that better soil quality and crop nutrition attributed to hedgerow biomass might increase the herbivore populations in some cases. Thus, as Schroth et al. (2000) pointed out, the effect of agroforestry on pests may be context-specific and may depend not only on the type of crop but also on factors such as the specific pest and its microclimatic preferences.

Plant Diseases. As regards plant diseases, only a few reports are available on the disease incidence on specific crops grown in agroforestry vs. monoculture. MacLean et al. (2003) found that hedgerows increased the incidence of rice blast (*Pyricularia oryzae*) by decreasing air movement. In coffee plantations, Avelino et al. (2006) reported an increase in the incidence of coffee rust (*Hemileia vastatrix*) in shaded than in the open stands. Based on a comprehensive review of literature on shade management of coffee and cacao systems, Beer et al. (1998) posited that increased shading might favor black pod (*Phytophthora palmivora*) disease of cacao and other economically important fungal diseases (e.g., *Mycena citricolor* in coffee). Overall, agroforestry conditions seem to favor the incidence of plant diseases over insect pests.

Weeds. Available information on the extent of weed infestation in agroforestry vs. monoculture suggests that weeds are generally less abundant under agroforestry. Some research during the 1990s in Kenya and Nigeria reported an important shift over time in the composition of weed species, from difficult-to-control grasses and sedges to easily controllable broad-leaved weeds, in alley cropping (Hedgerow Intercropping, HI), possibly as a consequence of shading by the hedgerow and the smothering effect of the mulch (Jama et al. 1991; Siaw et al. 1991). The authors suggested the likelihood of HI reducing the weed seed bank in the soil over the years, especially if the hedgerow prunings were used as mulch, which would smother weeds, prevent further addition of weed seeds, and reduce seed germination. Kang (1993) reported from long-term trials in southwestern Nigeria that HI with gliricidia and leucaena reduced the infestation of perennial weeds, which are less dependent on the soil seed-bank, by the shading effect and probably allelopathy. Based on a meta-analysis, Pumarino et al. (2015) reported that agroforestry significantly reduced non-parasitic as well as parasitic weeds. In sequential agroforestry systems, this is because organic material incorporation from the trees and the resultant improvement of soil fertility may increase the crops' competitiveness against weeds and enable crops to outcompete weeds (MacLean et al. 2003). In simultaneous systems, shading by trees could be a factor in suppressing weeds. The beneficial effects of agroforestry may also be due to the moderation of microclimate by trees. For instance, in experimental studies, the emergence and occurrence of the parasitic weed striga (*Striga* spp.) decreased with soil temperature due to reduced germination (Carson 1989). Additionally, Midega et al. (2013) demonstrated that covering the soil with litter from plants significantly reduced the emergence of striga.

Summary. It may not be an overstatement to say that plant (crop) health issues are one of the important aspects of AFS that are appreciated more by experience and intuition than by scientific evidence. In the limited research that has been done on the topic, shade management has been considered a key factor affecting crop health (Loguercio et al. 2009; Andres et al. 2018). For example, the journal *Crop Protection* published a special issue "Crop HealthAgroforestry Systems" (https://doi.org/10.1016/j.cropro.2020.105187), volume 134, 2020, based on the presentations at the 4th World Congress of Agroforestry, Montpellier, France, (https://agroforestry2019.cirad.fr/), and perhaps that was the first publication of that nature on the subject of crop health issues in AFS. Out of the 12 research papers in the special issue, all except two were related to pests affecting coffee- and cacao-based AFS, primarily on the effects and interactions of shade management in those crops (Lamichhane 2020). Thus, a detailed treatment of plant health issues in AFS has, unfortunately, not received the deserving attention in AFS research and development.

22.6 Opportunities for Agroforestry Hot Spots as Biodiversity and Ecotourism Attractions

The eye-and-soul-catching natural beauty provided by the meticulously maintained agroforestry assemblages of trees and crops of various shades and shapes could be excellent ecotourism destinations for modern urbanites. Ecotourism, defined by The International Ecotourism Society, TIES (https://ecotourism.org/) as ***"responsible travel to natural areas that conserves the environment and sustains the well-being of the local people"*** offers tourists an insight into the impact of human beings on the environment and fosters a greater appreciation of our natural habitats, is rapidly becoming a major touristic opportunity that fulfills the desire for leisure in harmony with nature. Although the excellent television and movie documentaries that are abundantly available bridge some of the growing gaps of understanding between humans and nature, they are no substitutes for the unique opportunities provided by programs such as ecotourism for immersion into nature and experience, first-hand, the intricacies of sustainable management of natural resources for simultaneous production of food and wood on traditional agroforestry farms. Several well-known homegarden systems of the tropics described in Chapter 7 such as those of Kerala, India; Java, Indonesia; Kandy, Sri Lanka; the Chaaga system on the foothills of Mount Kilimanjaro in Tanzania, and others are already popular ecotourism attractions (Figures 22.9 and 22.10). Contrary to "overtourism" that harms communities by overuse and destruction of resources through overcrowding and commercialization, well-planned ecotourism and ecodevelopment operations centered around agroforestry have excellent potential for further

Figure 22.9 Agroforestry and ecotourism hotspots: The backwaters of Kerala, India, are a delightful ecotourism destination. The floating houseboats made of all-natural materials traverse the tranquil waterscape surrounding the Agroforestry Homegardens dominated by coconut palms and spice trees. The boats are staffed with ecotourism guides and have modern overnight bedrooms and a kitchen and pantry with chefs. Source: AdobeStock_243679274 (with permission)

Figure 22.10 Agroforestry and ecotourism hotspots – Tea gardens of Munnar, Kerala, India. Tea (*Camellia sinensis*) bushes under the light shade of a scattered stand of *Grevillea robusta* trees. (Stock Photo)

promotion. It is high time that the exploitation (not in a pejorative sense of the word) of such untapped ecosystem services of agroforestry gets on to the operational agendas of development planners.

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Section VI

Sustainable Development, Agroforestry, and Land Management in the Future

Food Security, Agroforestry, and Sustainable Development Goals

23

Contents

Abstract

This chapter examines the role of agroforestry systems (AFS) in fulfilling the demands and expectations of food security and the related United Nations Sustainable Development Goals (SDGs). These issues are particularly focused on developing countries, where the predominance of small farms is a distinguishing feature. The definition of a small farm is variable depending on the country, but agroforestry is a common practice – indeed a way of life – for most of the smallholder farmers in developing nations. A consensus is now emerging that multifunctional agriculture that increases food production while simultaneously enhancing social and environmental goals, as committed to in the SDGs, is important not only for smallholders but the entire farming community. Consequently, the push for moving away from the narrow focus on yield toward diversified agriculture that respects and enhances broader societal and environmental goals is gathering momentum. Agroforestry has all the attributes of such a highly multifunctional land-use alternative. Food security has been a cornerstone of agroforestry right from the early days of its development. The lack of a quantifiable measure or index is a major difficulty in evaluating the impact of any land-use system or activity on food security. The major under-appreciated direct roles of agroforestry in ensuring food

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security include food-producing trees and nutritional security provided by diverse components and products of AFS. Diversification and rehabilitation of degraded farmland with species producing highly nutritious and marketable traditional foods will improve food production by conventional staple food crops and create new local business opportunities and enhance social well-being. Agroforestry thus offers an enormous opportunity for augmenting food security, but it needs new investments in research, besides institutional and policy changes.

23.1 Introduction

Food Security has been and continues to be one of the prominent items in the global development agenda. It is the second (listed as "Zero Hunger") among the 17 Sustainable Development Goals (SDGs: see Annexure I) set by the United Nations as the blueprint to achieve a better and more sustainable future for all by the year 2030 (UN General Assembly 2015). Indeed, the first among the SDG goals ("No Poverty") is so inseparably linked with food security that often both are even considered synonyms (Griggs et al. 2013). In the definition of the term food security adopted at the 1974 World Food Conference (www.fao.org/WFS) held in Rome, Italy, under the auspices of the UN Food and Agriculture Organization (FAO), the emphasis was on the supply of food. That definition was later expanded to include demand, access, and quality of food materials; and several definitions have since been proposed. The 1996 World Food Summit at Rome stated that food security exists "***when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life***." Thus, food security is a very complex issue involving the interplay of a large number of mega sectors including the production (quantity, variety, quality of food produced), access and availability (acquisition, transportation, processing, storage, and distribution), and safety (nutritional standards) of food. This chapter primarily examines the role of agroforestry systems in fulfilling the demands and expectations of food security and, *inter alia,* the related SDGs.

Food security, and indeed the SDGs in general, are particularly focused on the developing world (UN General Assembly 2015). The FAO (2017) statistics show that globally 1.9 billion people (about 25% of the total population) are food-insecure. Of these, about 850 million (about 11% of the total) are undernourished, with sub-Saharan Africa (about 21.7% of the people of the region), South Asia (10.8%), and Southeast Asia (8.3%) accounting for the majority of them (Figures 23.1 and 23.2). Food security is most critical in these regions. The predominance of small farms is one of the distinguishing features of agriculture in these developing countries (Graeub et al. 2016; IFAD/UNEP 2013). Although the definition of a small farm (and a smallholder farmer, a term sometimes erroneously and even belittlingly mentioned as "small farmer") is variable depending on the country, a majority of the smallholder farmers in developing nations live in poverty (World Bank 2015). Globally, about 84% of the farms are smaller than 2 ha. While there is a consensus that these small farms contribute substantially to global food production (FAO 2018), there is no unanimity of views on the share of small farm contribution to the total. According to FAO (2014), smallholders produce 70–80% of the world's food; but other reports disagree. For example, Lowder et al. (2016) argue that it is implausible that with only 12% of the world's land, small farms, defined as those operating less than 2 ha, can produce a large share of the world's food. Riccardi et al. (2018) indicated that such farms (<2 ha in size) accounted for 28–31% of global crop production and 30–34% of global food supply on 24% of gross agricultural area. It seems that, since the definition

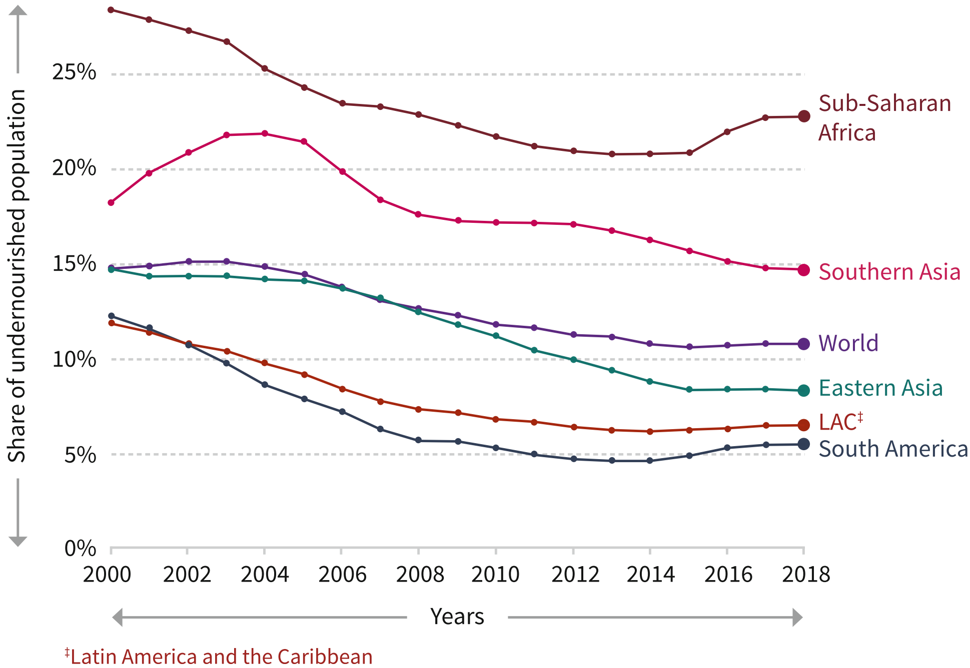

Figure 23.1 Percentages of undernourished people in different parts of the world, 2000–2018. Note: Undernourishment measures the share of the population that has a caloric intake which is insufficient to meet the minimum energy requirements necessary for a given individual. Source: FAO (2017)

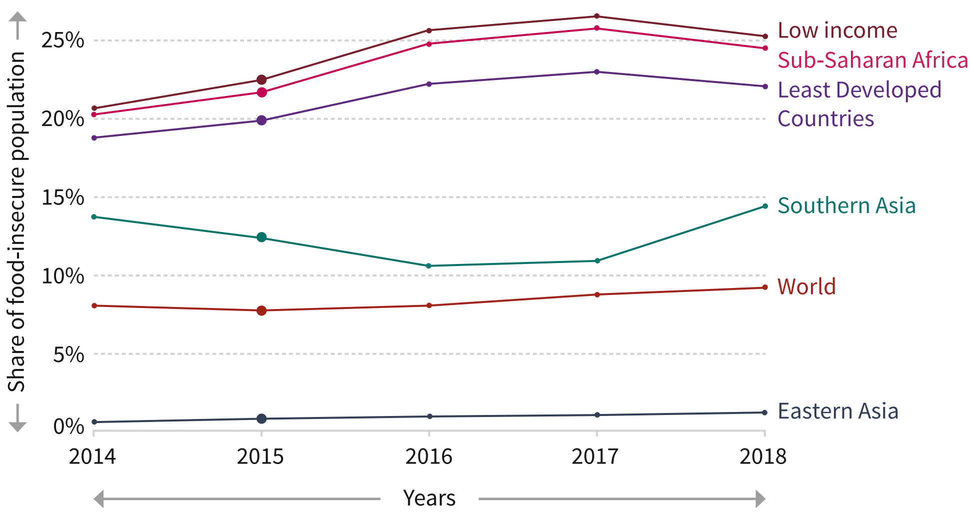

Figure 23.2 Share of population with severe food insecurity in different parts of the world, 2014 to 2018. Note: Food insecurity is defined by the Food Insecurity Experience Scale (FIES). Severe food insecurity is more strongly related to insufficient quantity of food (energy) and therefore strongly related to undernourishment or hunger. Source: FAO (2018)

of a small farm varies depending on the country, a universally acceptable definition of the area of a small farm and, therefore, the share of the "small-farm contribution" to global food production, are not critical issues. But it needs to be recognized, as Lowder et al. (2016) have articulated, that in countries at lower levels of income, smaller farms operate a far greater share of farmland than do smaller farms in the higher-income countries. It is also worth noting that although the greatest number of food-insecure people are in sub-Saharan Africa and South Asia, moderate food insecurity is a major issue across all regions, even among the high-income countries. Thus, access and affordability of diverse, nutritious diets are important for all countries.

23.2 Agroforestry and Food Security

While conventional, monocultural agriculture considered to be the mainstream approach to food production has helped increase agricultural production and avoid large-scale hunger, it has also caused extensive environmental and social harm as discussed in Chapter 1 (Section 1.2). This fact is slowly and steadily being acknowledged, though much less accepted, by the powerful institutions and individuals around the world. A consensus is emerging that what is needed and appropriate is "multifunctional" agriculture that increases food production while simultaneously enhancing social and environmental goals, as committed to in the SDGs – an agricultural paradigm that is more resilient to multiple insecurities including climate change, soil degradation, and market unpredictability, all of which reduce sustainability and are likely to exacerbate hunger (Montgomery 2007; Morton 2007; Stern 2007; Foley et al. 2011; Leakey 2020). Consequently, the push for moving away from the current, narrow focus on yield, toward the multifunctional agriculture that not only respects but enhances broader societal and environmental goals is gathering momentum (Godfray and Garnett 2014; Maxwell et al. 2016; Waldron et al. 2017; Willett et al. 2019). The SDGs provide a broad and coherent framework for multifunctional agriculture, since this international agreement already combines food security (SDG#2) with environmental, climate, and social goals and indeed emphasizes the need for a multigoal approach (Pretty and Bharucha 2014; Willett et al. 2019).

Agroforestry has all the attributes of such a highly multifunctional land-use alternative (Garrity et al. 2010; Leakey 2014). Food security has been a cornerstone of agroforestry right from the early days of its development. As described in Chapter 1, the interest in modern agroforestry arose from the appreciation of the traditional ways of growing trees and crops together sustainably from the same unit of land that smallholder farmers have been practicing for generations but had been ignored or bypassed in the push for developing monocultural high-input agricultural systems. Food production, not only from short-duration crops but also from the various fruit- and nut-producing trees that were grown in intimate agroforestry combinations, was always an essential aspect of agroforestry. The traditional agroforestry systems described in Section II of this book such as homegardens (Chapter 7) and the various localized systems (Chapter 11) provide excellent examples of systems that fulfill the concept of "physical, social, and economic access to sufficient, safe, and nutritious food to meet the dietary needs and food preferences" ingrained in the expanded definition of food security described earlier. Thus, the provision of food security is an essential function of agroforestry.

The linkage between agroforestry and food security is both direct and indirect. A unique characteristic that strengthens the food security attribute of agroforestry compared to monocultural systems of agriculture is that the desirable trees when grown in combination with crops and animals provide both direct (production) and indirect (service) contributions toward food security. Direct ways include those related to production, availability, and safety (nutritional standards) of food, while the indirect linkages exist between food security and the various ecosystem services of agroforestry including soil productivity and protection, carbon sequestration and climate change mitigation, biodiversity conservation, and augmentation of social and societal values. These ecosystem services have been discussed in detail in Sections IV and V (Chapters 16 to 22) of this book. An interesting illustration of these direct and indirect contributions of the multifunctional agroforestry systems in comparison with those of the conventional (monocultural) systems, proposed by Waldron et al. (2017) is presented (with permission) as Figure 23.3. The figure, however, only identifies the various avenues or connections but does not show the relative importance or contribution of each.

Indeed, the lack of a quantifiable measure or index is a major difficulty in evaluating the impact of any land-use system or activity on food security. Food security remains more of a concept embodying as well as influenced by numerous factors, many of which cannot be measured or expressed in quantitative terms. Solving the problems of food security requires a range of interconnected land-management approaches involving biophysical and socioeconomic issues, some of which cannot be fully expressed in quantitative terms. The definition ("physical, social, and economic access to sufficient, safe, and nutritious food to meet the dietary needs and food preferences") is too broad and vague involving both measurable parameters and intuitive (non-measurable) "feelings." Although an Internet search of the literature on the role of agroforestry on food security brings

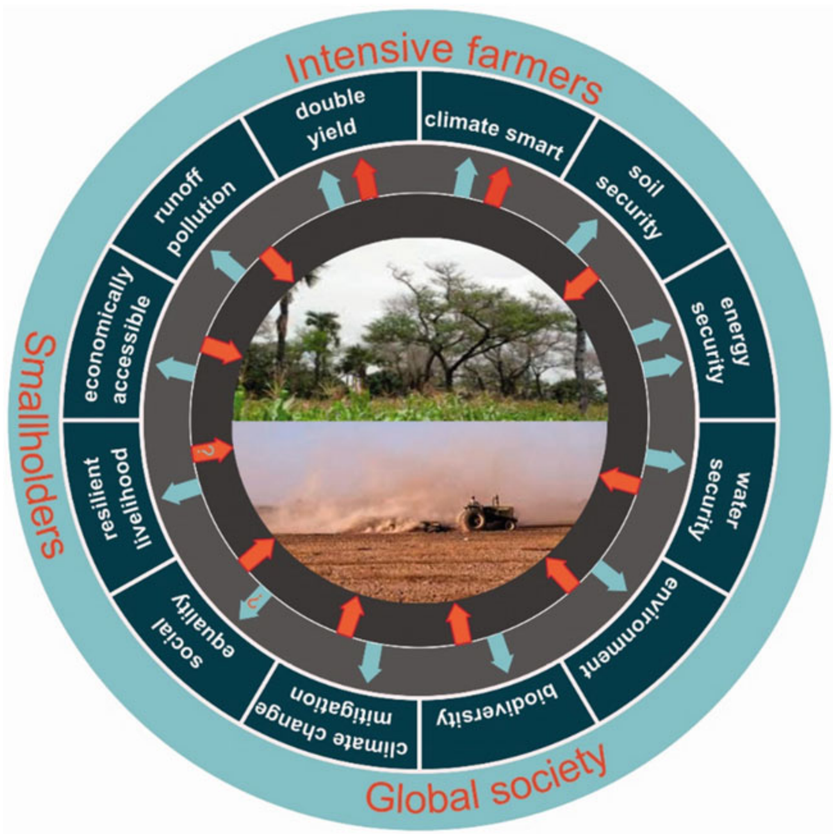

Figure 23.3 Achievement of multiple goals through agroforestry (top photo) and conventional agriculture (bottom photo). Twelve goals are shown, all related to food security (especially for developing-world agriculturalists) and to other sustainable development goals connected with agriculture. Arrows compare how agroforestry (lighter blue) and conventional intensification (darker red) affect each goal: Arrows pointing away from the circle center indicate a likely positive impact on the goal, vice versa for arrows toward the center. To reflect uncertainties, arrow heights are arbitrarily equal. Source: Waldron et al. (2017)

out hundreds of references including many from well-respected and widely quoted authorities, they all are more or less of the same "tone" – articulating convincing reasons as to why agroforestry weighs heavily on food security or describing site-specific examples of "flourishing" agroforestry examples of highly food-secure systems, but none projecting comparative studies of different systems for their food-security worthiness. The situation is somewhat similar for assessing the role of agroforestry in providing various ecosystem services too, such as biodiversity conservation, climate change mitigation, cultural and social services, and so on. The effects of all these services are "felt" and perceived but have not been quantified; maybe they are not quantifiable entities. With that caveat, let us examine the major direct roles of agroforestry in ensuring food security.

23.3 Direct Role of Agroforestry in Food Security

23.3.1 Fruit Trees

The indigenous farming systems of many developing countries often include many fruit- and nut-producing trees. Table 23.1 gives the numbers of trees in ***The Agroforestree Database*** reported as providing food and nutritional security as well as other products and services to smallholder farmers in the three major developing regions of the tropics. [*The Agroforestree Database* (www.worldagroforestry.org/resources/databases/agroforestree) is an open-access database maintained by ICRAF containing data on a wide range of products and services provided by a total of 650 trees that are of interest to farming communities in different geographical regions in the tropics.] Many of the species included under the category "human food" are common components in most homegardens and other mixed agroforestry systems; they are also integrated with arable crops either in intercropping mixtures or along boundaries of agricultural fields. These fruit trees (a combined term for fruit- and nut-producing trees) are well adapted to local conditions and are extremely important to the diet and economy of the people of the region, some of them are seldom known outside their common places of cultivation. For example, an inventory of the commonly cultivated plants in mixed agroforestry systems in Tomé Açu, near Belém, Brazil listed 32 fruit-producing species, a majority of which were indigenous trees virtually unknown outside the region (Subler and Uhl 1990). Examining the biological and socioeconomic attributes of fruit trees and their role in agroforestry systems, Nair (2007) concluded that fruit trees are one of the most promising groups of agroforestry species. Condensed species profiles (characteristics) of the common fruit trees in tropical agroforestry systems are given in Table 23.2. The table gives only some general information on some species. As Table 23.1 shows, numerous

Table 23.1 The numbers of trees in ***The Agroforestree Database***[1] reported as providing food and nutritional security as well as other products and services to smallholder farmers in the three major developing regions of the tropics

	Regions			
Function	Africa	South America	Southeast Asia	Total (regions)
Human food	295 (54)	119 (43)	225 (49)	639 (50)
Animal fodder	295 (55)	96 (45)	191 (47)	582 (50)
Soil improvement	194 (510)	73 (45)	154 (45)	421 (48)
Fuel	357 (53)	126 (42)	249 (47)	732 (49)
Total (functions)	1 141 (53)	414 (43)	819 (47)	2 374 (49)

[1]*The Agroforestree Database* (www.worldagroforestry.org/resources/databases/agroforestree) *is an open-access database maintained by ICRAF containing data on a wide range of products and services provided by a total of 650 trees that are of interest to farming communities in different geographical regions in the tropics.*

Note: The numbers in parentheses indicate the percentages of indigenous species. The category "Human food" includes fruits, nuts, and such other products that are good for direct consumption; those under the categories "Animal fodder" and "Soil improvement" contribute indirectly to food security; and "Fuel" refers to provision of fuelwood and charcoal for cooking and other forms of food processing. Considering that the total number of all species in the database is 650, it is evident that many species perform multiple (more than one) functions. The data illustrate the smallholders' use of indigenous and exotic species in almost equal proportions

Table 23.2 Condensed species profiles of some tropical and subtropical fruit and nut trees for agroforestry systems

Species	Ecology								
			Adaptability						
Common (English) and Scientific names and Family	Plant type/ Growth form	Ecozone / Distribution	Climate	Soil	Other	Management	Functions/uses	Common AF systems/ practices involving the species	Other remarks
Allanblackia (Tallow tree) *Allanblackia floribunda* Clusiaceae	An understory, evergreen tree in rainforests, straight bole, up to 25 m high.	West to Central Africa.	Temp 24–33 °C, 1200 to 2400 mm rain.	Leached acid soils, pH 4.0 and above.	Germination takes 6–18 months. Large fruits.	Dioecious: male and female forms grown together; fruit bearing in 12 year; fruits mature on tree and collected when they fall.	Used for long in African medicine; oil is of high quality and in great demand. Fat from seed is used in cooking, cosmetics.	Used as shade for cacao. Efforts are under way to domesticate the species and exploit its potential.	*A. parviflora* is a similar tree, used to be treated as the same.
Avocado *Persea americana* Mill. Lauraceae	Spreading tree of 10–15 m; thick evergreen foliage; broad leaves.	Native to mountainous Mexico; wide distr. Esp. tropical highlands.	Up to 2000 m in tropics; 15–25 °C; rainfall up to 1500 mm.	Deep well-drained soils; pH 5.0–8.0; fertile soils preferred.	Can tolerate drought, but not flood and frost.	Propagated by stem cuttings; about 400 trees/ ha; starts bearing in 5 year; usually no pruning.	Fruit weighs up to 250 g; edible; mainly eaten raw; edible buttery pulp with 25–30% oil; “poor man’s butter.”	Commonly grown with other fruit trees in tree gardens and homesteads.	Thick canopy allows little light to understory; foliage is a good mulch.
Breadfruit *Artocarpus altilis* Fosberg Moraceae	Monoecious tree up to 20 m; ever-wet areas; deciduous in monsoon areas; profuse foliage.	Native to Polynesia; grows well in hot humid tropics, esp. in Asia and the Pacific.	Tree of hot humid lowlands; 150–250 cm rain; 22–35 °C.	Wide range; prefers deep, well-drained soils.	Does not grow in shallow or waterlogged soils.	Vegetative prop. by root cuttings; usually no seed setting; planted 8–10 m apart; bears in 3–5 year; needs little care.	Edible starchy fruits, 700 fruits/tree/year produced all year round; vegetable or cooked; biscuits also made; timber useful for farm uses.	Grown mixed with several other spp. in homesteads; offers shade for livestock and crops like taro.	Sometimes a staple food in the Pacific Is. and the Seychelles.
Brazil nut *Bertholletia excelsa* Humb.	A tall, large tree up to 40 m; straight trunk, short-stalked,	Grows mostly in the Amazon forests, not	Wet hot Amazonia; attempts to introduce to	In the native habitat, the soil is	Does not tolerate shade but tolerates understory.	Seed-propagated; fruiting in 10–15 year. Fruits	Fruits (swollen hypocotyl) an important nut of commerce in the	Can grow in association with several other species. Can be	Popular fruit-, and timber, overstory species of the

(continued)

Table 23.2 (continued)

Species	Ecology								
			Adaptability						
Common (English) and Scientific names and Family	Plant type/ Growth form	Ecozone / Distribution	Climate	Soil	Other	Management	Functions/uses	Common AF systems/ practices involving the species	Other remarks
et. Bonpl. Lecythidaceae	large leaves; long-lived.	popular in other areas.	W. Indies, SE Asia not successful.	acid, fertile forest soils.		fall off naturally. Edible portion is the swollen hypocotyl inside a thick, hard shell.	Amazonia region; timber very valuable.	a good overstory species for coffee, cacao, etc.	Amazon region.
Carob *Ceratonia siliqua* L. Leguminosae (Fabaceae)	A dioecious tree of medium height 10–20 m.	Cultivated mainly in the Mediterr. Region.	Cool dry Mediterr. climate; 10–30 °C; low rainfall.	Deep, fertile loams; pH above 7.0	Can withstand drought; tolerates salinity.	Propagation by seed; transplanted; first bearing in about 12 years; produces about 12 t/ha/year.	Pods rich in sugar and protein; edible fruit flesh; used in confectionery; valuable forage for animals and bees.	Used widely in silvopastoral system; in anti-erosion hedges; windbreaks.	Known also as St. John's bread; produces useful gums.
Cashewnut *Anacardium occidentale* L. Anacardiaceae	Spreading evergreen tropical tree up to 12 m; tree canopies up to 10 m diameter at maturity.	Widely distributed in tropics; Brazil, India, East Africa.	Up to 1300 m; 300–1500 mm rainfall p.a.; needs dry weather for flowering and fruiting.	Wide soils range; grows in infertile and rocky areas, pH 5.0–8.0.	Tolerates poor soils and areas with dry spells; does not tolerate floods; lives up to 50 year.	Seed-propagation; sown at stake; also veg. Prop. by layering or grafting; about 10 m^2 spacing; very little aftercare; bearing in 7–10 year.	Highly priced kernels used in confections and desserts; shell-oil has industrial uses; cashew apple is juicy and edible, used for winemaking; firewood.	Cattle grazing under cashew; tree gardens in smallholdings; used as a windbreak and shelterbelt.	Drought resistant tree; non-synchronized flowering; difficulty in collecting nuts.
Coconut palm *Cocos nucifera* L.	Tree up to 30 m; erect, unbranched stem; crown of	Coastal tropical areas; South & SE Asia;	Mean temp. 27 °C ± 7 ° C. Well-distributed	Well-drained, deep soils; pH 5.0-	Tolerates salinity; does not tolerate	Prop. by planting one-year-old seedlings; about	Edible oil from copra (dried endosperm); fruit; drink;	Many types of crops grown under or between palms;	Most widely cultivated palm–alone or with other

Arecaceae (Palmae)	long leaves with slender leaflets; apical growth.	African coast; Caribbean Islands.	rainfall; > 2000 mm p. a.	8.0, common in coastal sands and loams.	prolonged flooding.	175 palms/ha; full bearing from about 8 to 75 year; responds well to manuring	leaves for thatch and weaving; many minor products; acclaimed "Tree of Heaven."	multistorey cropping; grazing under coconuts is common.	crops; many types and cultivars.
Custard apple (sweetsop or sugar apple) *Annona squamosa* L. Annonaceae	Woody shrub or small tree of 5–6 m height.	Native to tropical America, now grown throughout tropics, esp. SE Asia.	Humid tropics of low to medium altitudes; 20–30 °C.	Deep fertile well-drained soil of pH 5.0–8.0	Can tolerate some drought.	Seed-propagated; fruiting starts in 3–4 years; fruit-set can be enhanced by hand pollination; fruits 7–10 cm in diameter and very perishable.	The custard-like granular pulp in which the seeds are embedded is edible; bark produces tannin; offers light shade for understory species.	Usually a plant of the backyard where grown mixed with large number of other spp.; yields about 10 t fruit/ ha/year.	A very similar fruit *A reticulata*, (bullock's heart), is also known as custard apple.
Date palm *Phoenix dactylifera* L. Arecaceae (Palmae)	Tall palm, up to 30 m; unbranched stem covered with leaf remains; dioecious inflorescence.	Grown mainly in the Arab countries, India, N. Africa, Mexico.	Temp (26–45 °C), low humidity; typical of the Middle-East vegetations.	Loam and sand of pH above 6.0, shallow, responds to N.	Tolerant to drought and salt in root zone.	Vegetative prop. by basal axillary shoot (suckers); many cultivars; artificially pollinated.	Edible fruit (20–100 kg/tree/ year); sap for wine; leaves for thatch, weaving; trunk for wood; many minor products; shelterbelts and for sand dune fixation.	Grown as an overstorey species in oasis and other arid regions; large number of crops grown underneath.	It is said to have about 800 different uses.
Doum palm *Hyphaene thebaica* (L.) Martin Palmae	Tall palm; up to 15 m; branched fan palm.	Mainly in semi-deserts and deserts in Africa.	Semi-arid to arid; hot, dry climate up to 600 m altitude.	Deep sand or alluvial, or pH > 6.0.	Tolerant to drought and salinity.	Seed-propagated; germination very poor; transplanted; bearing in about 10 years.	Fruits are edible; edible heart; sap for wine; fruit for medicinal use; leaves for weaving.	Vegetables and other crops grown as understory.	Also known as gingerbread palm.
Drumstick (Horseradish tree)	Small, branching tree, up to 8 m;	Lowland humid trop. of S and SE	Hot humid lowlands (20–35 °C);	Fertile well-drained;	Does not tolerate water logging.	Prop. by seed; bears slender long (~ 60 cm)	Tender fruits cooked as a veg; tender leaves	Grown mixed with other spp. in	An under-exploited species; now

(continued)

Table 23.2 (continued)

Species	Ecology								
			Adaptability						
Common (English) and Scientific names and Family	Plant type/ Growth form	Ecozone / Distribution	Climate	Soil	Other	Management	Functions/uses	Common AF systems/ practices involving the species	Other remarks
Moringa oleifera Lam. Moringaceae	sparse canopy; small leaves.	Asia, Pacific Islands.	1500 mm well-distrib rain p.a.	deep, soils; pH 5.0–7.0.		fruits (1.5 cm dia.) when 3-year-old; weak stems; trees toppled by winds.	used as a spinach; leaves have medicinal value in local medicines.	homegardens; hedge/border plant, and for light shade.	popularized in Africa.
Durian *Durio zibethinus* Murr. Bombacaceae	Medium to large tree up to 30 m; fruit is a large ovoid capsule, borne on stem up to 30 cm long; 15 cm diameter.	Lowlands of SE Asia; attempts to grow it in other places of similar climate not successful.	Humid tropical lowlands (> 150 cm rain p.a.); 25–40 ° C; up to 800 m.	Deep, well-drained acid fertile soils: loam or sand; pH <5.0.	Tolerates drought to some extent; does not tolerate water stagnation.	Prop by stem cutting/ grafting; seeds have short viability; bearing in 7 year.; needs very little care/ mgmt.; fruit does not mature until falls from tree.	Fruit is famous, but its smell and flavor disliked by many; provides important revenue to villagers; a useful tree of the backyard.	Usually a smallholder home-grown crop; grown mixed with a large no. of other plants.	Durian is a famous fruit, liked and disliked by many; liked very much by wild animals.
Guarana Sapindaceae *Paullinia cupana* Kunth.	Perennial woody vine, but the cultivated form is a thick-foliaged shrub.	Native to Amazon basin; not grown in other areas.	Warm humid climates; up to 800 m; well-distrib rainfall.	Grows in latosols with a thick layer of organic matter.	Little tolerance to long dry periods as well as floods.	Prop by seeds (very short viability); young plant trailed on trellises; needs pruning; flowering in first year.	Seeds contain 4– 6% caffeine; dried powdered seeds used for cakes; source of caffeine in soft drink manufacture.	Grown under the shade of large trees, with cacao and coffee AFS in Brazil.	Guarana has many medicinal properties.
Guava *Psidium guajava* L. Myrtaceae	Shallow-rooted large shrub or small spreading	Widely distributed in the tropics from sea	15–35 °C; low humidity; 500 –	Variety of soils, deep loam, pH 5.5 –	Tolerates drought and floods; but not salinity.	Prop. veg or through seeds; regular pruning to shape the	Fruits vary in size and flavor; eaten raw or preserved; fruits	Grown with a other spp. in the homegardens and tree gardens	In some places (e.g. Fiji), it has been declared as a weed.

	tree, 3–10 m; low-branching.	level to 1500 m.	1500 mm rain p.a.	7.5 preferred.		trees and remove and suckers; fruiting in 2 year; up to 30 year.	rich in vitamin C; average yield about 100 kg/ tree p.a.	as a middle layer canopy.	
Jackfruit *Artocarpus heterophyllus* Lam. Moraceae	A monoecious evergreen tree up to 20 m; one of the largest cultivated fruits (up to 30 kg/ fruit).	Native to trop India; grows in S and SE Asia, Caribb. & and Pacific Is.	Hot humid tropcal lowlands up to 800 m; rainfall above 150 cm p.a.	Deep, fertile loam or sandy loam; pH 5.0–7.0.	Tolerates drought and floods to some extent.	Seed propagated, but also by layering and grafting; fruiting in about 8 year, lasts up to 60 year; needs very little care.	Fruit for dessert; unripe fruit is a vegetable; leaves eaten by goats; timber valuable for furniture and housing; firewood.	Grown mixed with other species in the backyard; used for penning cattle underneath; good for border.	Thick foliage does not allow much light to the understory.
Kola nut (Cola nut) *Cola nitida* (Ven.) Schott & Endl. Sterculiaceae	*C. nitida* is 10–15 m tall; unbranched in lower part; large leaves.	Mostly in humid W. Africa; also W. Indies, India, Brazil.	Humid trop. Climates, > 150 cm rain with dry seasons; up to 800 m.	Light, well-drained, fertile soils; pH 5.0–7.0.	Tolerates drought and flood, but not salinity.	Prop. by seed; germinates in 7–12 weeks; grows in flushes; fruiting from 7 to 80 year.	Av yield 250 kg/tree; Seeds used as stimulants and beverages; contain 2% caffeine and some essential oils.	Interplanted with fruit trees in the young ages and with other tree species in the adult stages.	Fruit is erroneously called "nut." Several spp. of kola trees.
Litchi *Litchi chinensis* Sonn. Syn. *Nephelium litchi* Camb. Sapindaceae	Small to medium tree, I0–20 m high dense canopy; evergreen.	Sub -tropical to tropical China, northern India; 1000–2000 m.	Moderate climate: 15–35 °C; high altitudes; cool dry season for fruiting.	Deep, well-drained loams; pH 5.0 – 7.5.	Tolerates drought and occasional floods; fails to fruit in lowland tropics.	Propagated vegetativey, mainly by air-layering; trees start bearing in 4–6 year.	The fruit is a nut; the the juicy aril that surrounds the nut is the edible part; eaten raw or preserved aril is also dried to produce litchi nuts.	Useful as a windbreak, bee forage; also grown mixed with other fruit trees.	An ornamental plant.
Longan *Dimocarpus longan* Lour. Syn. *Euphoria longan* (Lour.)	Small to medium tree; 10–20 m high	Mainly in warm humid parts of S and SE Asia.	Humid, lowland trop; well-distributed rain; 20–	Deep, well-drained fertile loam;	Does not tolerate drought or salinity; can withstand	Propagated mostly by seed; comes to fruiting in 6–8 year.	Fruit eaten raw or cooked; the mucilaginous flesh is whitish, translucent and	Grown with other fruit trees and also vegetables;	Medicinally important.

(continued)

Table 23.2 (continued)

Species	Ecology								
			Adaptability						
Common (English) and Scientific names and Family	Plant type/ Growth form	Ecozone / Distribution	Climate	Soil	Other	Management	Functions/uses	Common AF systems/ practices involving the species	Other remarks
Steud. Sapindaceae			35 °C; up to 1000 m	pH 5.5–7.0.	some flooding.		somewhat sweet.	common in homegardens.	
Macadamia nut *Macadamia integrifolia* Maiden et Betche Proteaceae	Small to medium tree; 10–15 m.	Native to Australia, but mainly cultivated in Hawaii	Warm moderate climate; 15–30 °C with occasional rains.	Deep, well-drained loam; pH 5.5–7.5.	Tolerates drought and occasional floods.	Propagated by stem cutting or grafting.	Fruits are the macadamia nuts of commerce; rich in protein and fat; also produces oils and tannins.	Can be grown with other fruit trees; good for bee forage; also border planting.	Also known as Queensland nuts or Australian hazel nuts.
Mango *Mangifera indica* L. Anacardiaceae	Medium to large evergreen tree to 20 m height.	Native to India; very popular in India, but also in SE Asia, Africa, and tropical America.	Wide range of climate from lowlands to highlands; warm, dry to hot humid.	Deep fertile loam to infertile, well-drained sand; pH 5.0–8.0.	Tolerates drought and seasonal floods.	Prop by seed or layering and grafting; pruning for shape and induce flowering and branches; full bearing in about 8 years., up to 50 years and more; several cultivars and hybrids.	Fruits delicious, dessert; immature fruits in chutneys and pickles; ripe fruits as preserves; branches for farm construction; used in dyes.	Grows with other fruit trees in the backyard; good as a border/ shelterbelt species; cattle penning in the shade; animal feed or forage.	Several forms and types are popular; used extensively on the landscape in India, E. Africa.
Mangosteen Guttiferae *Garcinia mangostana* L.	Slow-growing glabrous, evergreen medium tree to 12 m; compact conical shape.	Native to Indonesia Malaysia; introduced to Australia, India, and elsewhere.	Hot, humid lowland climate with a well-distributed rainfall.	Well-drained fertile deep soil, pH below 6.0.	Can withstand dry spells.	Seed-propagated; seeds poor viability; veg. Prop. not successful; requires shade when young;	A preferred, delicious fruit; fruits eaten fresh; the shell of fruits is rich in tannins, used for leather tanning and	Usually grown with other fruit trees and homegardens; 500–600 fruits/ tree/year.	Tendency for alternate bearing; difficult to propagate; long juvenile phase.

						bearing in 10-15 year. Lives up to 50 year.	medicinal purposes.		
Nectarine *Prunus persica* var. *nucipersica* (Suckow.) C.K. Schneid. Rosaceae	Low to medium sized tree; very similar to the peach tree, but having pubescence.	Grows in tropical highlands and sub-tropics.	Tropical highland to subtropical climate; 15–35 °C; low rainfall.	Well-drained deep sandy or loamy soil over clay; pH 5.0–7.0.	Can withstand drought, wind and shade.	Developed from a seed or bud of the peach as a mutant; prop by graft or root stock; starts bearing in 2–3 years; pruning required.	Fruits delicious; a source of vitamins A and C, eaten raw, or cooked in conserves, jams, and pies; yields about 20 t/ha/year; used as a shade tree.	Grown with other fruit trees; used as a shade tree and for border planting.	Probably originated in China > 2000 year ago; cult'd in ancient Persia, Europe.
Oranges *Citrus* spp. Rutaceae	Low growing tree with a sparse canopy; various species and cultivars with diff. Forms and fruit types.	Very widely cultivated all over the tropics especially in not-so-wet areas.	Prefers warm dry climate with mild temp (20–30 °C) and low rainfall.	Deep, fertile loamy soils of around neutral pH.	Can withstand drought and, to some extent, wind, but not floods.	Propagated by stem cutting for budding or grafting; pruning is regular management need; first bearing in about 5 years after planting.	Edible fruits, juices, preserves, marmalades, etc.	Grown in commercial sole stands; also in mixed stands of homegardens; good for hedge planting.	Very well studied and commercially cultivated, several varieties.
Papaya, (Pawpaw) *Carica papaya* L. Caricaceae	A short-lived perennial, 2–10 m; unbranched, erect, soft-wooded, hollow stem with leaves at the apex.	All over the tropics; S. Asia, E. Africa, Hawaii are major producers.	Wide range of climate; up to 2000 m altitude; for 20–40 °C; low altitude for papain production.	Well-drained deep fertile soil; pH 5.0–7.0; loamy texture.	Does not tolerate flood or waterlogging and salinity.	Seed prop; transplanted; plants dioecious, so planted at high density and later thinned; flowering in 4–6 months; responds well to fertilizer..	Preferred delicious fruit; leaves and long petioles sometimes used for mulch or compost.	Found in almost all subsistence agri. Systems in association with various crops; good for hedge / border planting.	Commercial production usually as sole crop.
Pejibaye palm (Peach palm) *Bactris gasipaes*	Monoecious, feathery palm; slender stem;	All over Central and S. American	Hot humid lowlands	Well-drained clays of	Can tolerate dry spells, but	Propagated by seed or suckers; seed-	Edible fruit (4 t dry fruit/ha/year.); edible	Often grown with other fruit trees or over	Also known as *Pupunha*; widely

(continued)

Table 23.2 (continued)

Species	Ecology								
			Adaptability						
Common (English) and Scientific names and Family	Plant type/ Growth form	Ecozone / Distribution	Climate	Soil	Other	Management	Functions/uses	Common AF systems/ practices involving the species	Other remarks
H.B..K. syn. *Guilielma gasipaes* Arecaceae (Palmae)	up to 1 5 m; profuse suckering.	lowlands up to 1200 m altitude.	200 cm rain p.a.	medium fertility; acid soils, pH < 7.0.	not floods or salinity.	propagated plants mature in 6–7 year, last for up to 70 year.	heart of the palm; trunk for wood; animal feed; shade over coffee, cacao, Palm heart popular as salad.	coffee, cacao, *guarana*, etc. Also good as windbreak and border planting.	cultivated in AF mixes all over S. America.
Rambutan *Nephelium lappaceum* L. Sapindaceae	An evergreen bushy tree up to 15 m tall; fruits hairy, independent clusters.	Very common in the lowland humid tropics of SE Asia.	Hot, humid lowlands; 200 cm well-distributed rain p.a.	Deep, fertile loams; pH below 5.5.	Can tolerate dry spells and floods, but not salinity..	Seed propagated; but veg. Prop by budding possible; fruit in 5–6 year; 200–400 fruits per tree/year; longevity up to 60 year.	Edible fruit, eaten fresh; a bee forage and ornamental (bright red, hairy fruit, and intact crown).	Often grown with other fruit trees in the homesteads; good for border planting and as a windbreak.	SE Asia account for approx. 80% of the world production.
Sago palm *Metroxylon sagu* Rottb. Arecaceae (Palmae)	A flowering feathery palm growing in thick stands, I0–20 m tall, stout erect trunk.	Rain forest swamps of SE Asia and the Pacific.	Hot, humid, high rainfall, swampy areas of tropical Rainforests.	Swamps, deep loams, and clays.	Tolerant to flooding, and salinity, but not drought.	Prop by suckers or tillers; transplanted; flowering in 10–15 year, after which the palm dies.	Starch from trunk (300 kg/ tree); leaves for thatch; starch extraction from split trunks before flowering.	Good for swampy areas and for windbreaks.	Few cultivated and managed stands; starch exported.
Sapota, Sapodilla *Manilkara achras* (L.) syn. *M. zapota*, *M. zapotilla*,	Evergreen bushy tree up to 20 m.	Native to Mexico and C. America; now widely grown in SE Asia.	Hot tropical lowlands of varying rainfall.	Fertile, deep, uniform loams; pH below 7.0;	Tolerates drought, and, to some extent, floods and salinity	Usually prop by seed; but also stem cuttings and grafting; fruiting in 3-4 years; 2500–	Edible dessert fruit; eaten raw when ripe; latex from the stem contains 20-40% gum, the	Usually grown with other fruit trees and crops in the homestead; can be used for light	Very popular fruit in Asia and tropical America.

Achras zapota Sapotaceae				wide variability.		4000 fruits/tree/ year; latex obtained by tapping trunk once every 2-3 years.	raw material for chewing gum; durable wood.	shade and border planting.	
Shea butter tree *Vitellaria paradoxa* C.F. Gaertn. syn. *Butyrospermum paradoxum* (Gaertn. f) Sapotaceae	A small-to-medium-sized tree, 7–13 m; deciduous.	Abundant in Central and West African savannas.	Dry, hot equatorial savannas; low altitudes.	Dry lateritic slopes; pH above 6.0.	Tolerant to drought, but not to floods.	Usually prop by seed; about 8 m spacing; starts bearing in 12–15 year; fruits fall naturally and then collected.	Shea butter extracted from seed used as a cooking fat, medicinal ointment; shea oil from the nuts used in soaps, candles, cosmetics.	Grows in mixed stands with other species in the drier margins of savanna with pronounced dry seasons.	An underexploited species with vast potential.
Tamarind *Tamarindus indica* L. Leguminosae (Fabaceae)	A large tree over 20 m tall with light canopy and thick stem.	Considered native to dry parts of Africa and India; popular all over Africa, India.	Wide adaptability grows well in dry and wet areas mainly in low altitudes.	Wide adaptation, pH about neutral; deep, infertile soils preferred.	Withstands drought very well.	Propagated by seed; needs very little care; starts bearing in about 10 year; lasts for several decades; fruits are collected from tree or allowed to fall.	Mesocarp eaten fresh or preserved in syrup; used as a condiment and flavoring; produces gums and tannins; firewood; foliage and seeds are animal feeds.	Grows as an overstorey species in many agric. Lands; light canopy and nitrogen fixation are advantageous.	Grows wildly in drier savannas of Africa and all over India.

Source: Adapted from Nair (1993)

[1]The table gives only some general information on some species. As Table 23.1 shows, numerous trees that contribute to human food and nutritional security have been identified in different regions of the tropics; about 50% of them are indigenous and many of them are relatively little studied and known outside their native habitats

[2]The emphasis is on tropical species because food security is a serious issue mainly in the tropics

[3]Several databases and excellent publications are available on promising fruit trees in various ecological and geographical regions; to name a few: *Traditional Trees of Pacific Islands* (Elevitch 2006), *Specialty Crops for Pacific Islands* (Elevitch 2011), *Tropical & Subtropical Trees: An Encyclopedia* (Barwick 2004), *Tropical Fruits* (Samson 1986), *Fruits of Warm Climates* (Morton 1987)

[4]In addition to the *Agroforestree Database,* several other databases are also available (Table 23.3)

[5]Also see the Multipurpose Tree (MPT) profiles, Chap. 13

trees that contribute to human food and nutritional security have been identified in different regions of the tropics; about 50% of them are indigenous and many of them are relatively little studied and little known outside their native habitats. Describing the numerous fruit trees belonging to 36 botanical families in the western Amazonian flood plains, Smith et al. (2007) suggest that the western Amazon may well be the single richest edible fruit region in the world. Some of these fruits are already being harvested on a large scale and they are important to local economies, while others are being experimented with for possible commercial production. Several other databases and excellent publications are available on promising fruit trees in various ecological and geographical regions; to name a few: *Traditional Trees of Pacific Islands* (Elevitch 2006), *Specialty Crops for Pacific Islands* (Elevitch 2011), *Tropical & Subtropical Trees: An Encyclopedia* (Barwick 2004), *Tropical Fruits* (Samson 1986), *Fruits of Warm Climates* (Morton 1987). In addition to the *Agroforestree Database*, several other databases are also available (Table 23.3); also see the Multipurpose Tree (MPT) profiles, Chapter 13.

23.3.2 Nutritional Security

The food diversity offered by the rich and diverse nutritional content of the products of various trees and other species is another remarkable feature of food security provided by agroforestry systems such as the homegardens. While some of these species enter commercial markets, many of them do not and are consumed at the point of production. This leads to ambiguity in their production and consumption data; nevertheless, they contribute enormously to the sustenance and nutritional (food) security for the smallholder farmers as various field-level investigations across Africa and Southeast Asia have shown (Jamnadass et al. 2011; Catacutan et al. 2012). Exotic and indigenous fruits cultivated and managed in agroforestry systems are important foods in Africa, as illustrated by household surveys. In Kenya, for example, a 2004 survey of more than 900 households found that over 90% grew fruit, with at least one-quarter growing banana (*Musa* spp.), avocado (*Persea americana*), and mango (*Mangifera indica*). Over two-thirds of households reported fruit production harvested from at least four fruit species, while over half sold some fruits. Similarly, in a 2009 survey of more than 1,100 rural households in Malawi, at least half of them consumed mango and/or papaya (*Carica papaya*) and one-third consumed oranges (*Citrus sinensis*), among other fruit, most of which were harvested from their farms (World Agroforestry 2018). This is true in the South and Southeast Asia regions as well. Domestic animals, as well as arable crops that are grown in such homesteads, also contribute substantially to food security, quantitative data on the contribution of such age-old practices and traditions to household food security are meager. The (US) National Research Council (2015) predicted that with a projected global population of approximately 10 billion people by 2050, the demand for animal protein including meat, eggs, milk, and other animal products is expected to increase dramatically. In addition to subsistence and smallholder agroforestry operations, silvopastoral and other integrated tree – crop – animal production systems (Chapter 9, Section 9.7) practiced by family farms (Chapter 10, Section 10.3.5) and commercial operations in the temperate regions as well will have a significant role in ensuring enhanced food security (Table 23.4).

Table 23.3 Proximate food composition of important fruits, nuts and leafy vegetables of tree/shrub origin

Scientific name	Food name (English)	Edible portion coefficient	Energy (kJ)[1]	Water (g)	Protein (g)	Fat (g)	Carbohydrate (g)	Fibre total, dietary (g)	Fibre crude (g)	Ash (g)
Adansonia digitata	Baobab fruit, pulp, raw	0.23	1380	11.0	2.4	0.5	75.0		6.2	5.0
Anacardium occidentale	Cashew apple, raw			86.5	0.8	0.3			1.5	
Anacardium occidentale	Cashew nut, raw	1.00	2430	5.3	17.7	44.4	27.0	3.1		2.5
Annona cherimola	Cherimoya, pulp, raw	0.69	327	79.4	1.6	0.7	14.7	3.0		0.6
Annona muricata	Soursop, fruit pulp, raw	0.67	278	81.6	1.1	0.3	13.2	3.3		0.6
Annona reticulata	Custard apple, raw	0.58	458	71.5	1.7	0.6	22.8	2.4		1.0
Annona squamosa	Sugar apple, pulp, raw	0.46	405	73.4	1.8	0.3	19.3	4.4		0.8
Artocarpus atilis	Breadfruit pulp, raw	0.79	436	71.2	1.3	0.3	21.5	4.9		0.9
Artocarpus heterophyllus	Jackfruit, pulp, raw	0.29	384	75.9	1.6	0.5	18.9	2.2		0.9
Balanites aegyptiaca	Desert date, fresh, raw	0.57	467	70.4	1.8	0.3	24.1		2.0	1.4
Balanites aegyptiaca	Desert date, dried, raw	0.22	1300	17.3	4.2	0.6	68.6	5.3		4.0
Borassus aethiopum	Borassus, pulp, raw		266	82.7	0.8	0.1	13.6		2.0	0.7
Canarium schweinfurthii	Black olive, raw		1290	47.4	3.4	24.3	17.8		4.3	2.8
Carica papaya	Papaya, pulp, raw	0.62	152	89.8	0.5	0.1	7.3	1.9		0.4
Citrus aurantium	Orange, sour		172	89.2		Tr	9.9		0.4	0.5
Citrus latifolia	Limes, raw	0.84	173	88.3	0.7	0.2	7.7	2.8		0.3
Citrus lemon	Lemons, raw	0.66	164	88.9	1.1	0.3	6.6	2.8		0.3
Citrus paradisi	Grapefruit (pink, red), raw	0.50	142	90.9	0.6	0.1	7.0	1.1		0.3
Citrus reticulata	Tangerines, raw	0.74	235	85.2	0.8	0.3	11.5	1.8		0.4
Citrus sinensis	Orange, raw	0.73	199	86.8	0.9	0.1	9.3	2.4		0.4
Cocos nucifera	Coconut, mature, meat/flesh, raw	0.70	1600	43.1	3.6	36.9	6.1	9.3		1.0
Cocos nucifera	Coconut, immature kernel, fresh, raw	0.30	668	74.0	1.6	13.5	6.7		3.3	0.8
Dacryodes edulis	Bush butter/African pear pulp, ripe, raw		1010	63.1	3.5	21.0	9.4		1.6	1.4
Dialium sp.	Fruit, dried, raw		1080	34.8	2.9	0.9	57.0		3.2	1.2
Diospyros kaki		0.86	297	80.5	0.6	0.2	14.7	3.6		0.3

(continued)

Table 23.3 (continued)

Scientific name	Food name (English)	Edible portion coefficient	Energy (kJ)[1]	Water (g)	Protein (g)	Fat (g)	Carbohydrate (g)	Fibre total, dietary (g)	Fibre crude (g)	Ash (g)
	Japanese persimmon, pulp, raw									
Diospyros mespiliformis	African ebony, fruit, raw		550	66.6	1.1	0.8	29.1		1.2	1.3
Dovyalis caffra	Kei apple, pulp, raw		240	85.9	0.4	0.4	12.7		0.3	0.3
Eugenia (*Syzygium*) *jambos*	Roseapple, raw	0.72	237	85.1	0.7	0.3	12.2		1.2	0.6
Ficus sycomorus	Fig, fruit, raw		237	83.8	1.1	0.7	9.5		3.8	1.1
Flacourtia indica	Indian plum, pulp, ripe, raw		395	76.3	0.9	0.8	20.1		1.1	0.9
Garcinia kola	Garcinia, fruit pulp, raw		201	88.1	1.1	0.4	9.6		0.5	0.3
Garcinia livingstonei	African Mangosteen, raw		267	83.9	0.8	0.3	13.9		0.7	0.4
Grewia spp. (*Grewia villosa*)	Mallow raisin, raw		444	70.0	3.3	0.2	20.5	4.0		2.0
Hyphaene compressa	Doum palm, pulp, raw		492	69.4	0.7	1.2	23.9		3.6	1.2
Litchi chinensis	Litchi, pulp, raw	0.60	300	81.8	0.8	0.4	15.2	1.3		0.4
Macadamia integrifolia	Nuts, macadamia nuts, raw	0.31	3110	1.4	7.9	75.8	5.2	8.6		1.1
Mangifera indica	Mango, pulp, raw	0.71	274	82.7	0.5	0.2	14.2	2.1		0.3
Manilkara zapota	Sapodilla, pulp, raw	0.75	344	77.5	0.5	1.0	15.0	5.6		0.5
Moringa oleifera	Drumstick leaves, raw/boiled	0.80	334	76.9	8.1	1.4	6.1	5.1		2.4
Moringa oleifera	Drumstick, pods, raw	0.52	166	86.8	2.4	0.2	4.7	5.0		1.0
Morus alba	Mulberry, raw		249	84.6	1.3	0.7	11.0	1.7		0.7
Musa spp.	Banana, raw	0.64	396	74.9	1.1	0.3	20.3	2.6		0.8
Opuntia ficus-indica	Prickly pear, pulp, raw	0.67	165	88.4	0.7	0.3	7.3	2.6		0.9
Persea americana	Avocado pulp, raw	0.74	633	76.5	1.7	14.7	1.3	4.7		1.1
Phoenix dactylifera	Dates, pulp and skin, dried, raw	0.87	1340	16.3	1.8	0.9	71.9	7.6		1.6
Pithecellobium dulce	Manila-tamarind, fruit, raw		353	76.3	2.8	0.5	14.3	5.5		0.6
Psidium guajava	Guava, pulp, raw	0.78	238	82.9	1.0	0.4	9.5	5.6		0.6
Punica granatum	Pomegranate, raw	0.56	330	78.7	1.4	0.6	14.8	4.0		0.5
Rubus pinnatus	Raspberry, raw			84.4	1.4	1.9		0.2		

Sclerocarya birrea	Marula, fruit, pulp and skin, raw		218	86.3	0.7	0.5	10.4	1.2		0.9
Solanum betaceum	Tamarillo (flesh and seeds), raw	0.93	170	87.6	2.2	0.3	5.4	3.7		0.8
Syzygium cumini	Eugenia/Jamun fruit, raw	0.62	232	84.2	0.6	0.3	10.8	3.4		0.7
Syzygium guineense	Water berry, raw	0.50	288	81.9	1.3	0.7	13.2		1.9	1.0
Syzygium malaccense	Mountain apple, raw	0.77	134	91.2	0.5	0.2	6.3	1.5		0.3
Tamarindus indica	Tamarind, pulp, ripe, raw	0.47	1170	26.9	3.6	0.8	61.3	5.1		2.3
Vangueria infausta	Wild medlar, pulp, raw		483	69.0	1.5	0.4	24.3		3.7	1.2
Vitellaria paradoxa	Shea, fruit pulp, raw	1.00	413	73.3	1.5	0.9	19.1	3.7		1.5
Vitex doniana	Black plum, pulp, raw		476	70.1	0.4	0.3	26.3		1.4	1.5
Ziziphus mauritiana	Jujube pulp, raw	0.80	288	82.1	1.4	0.5	13.8		1.4	0.8

All data expressed per 100 g edible portion, fresh weight; [1]energy, total metabolizable; calculated from the energy-producing food components, *Tr* traces

Source: Adapted from Stadlmayr B, McMullin S, Jamnadass R (2019): Priority Food Tree and Crop Food Composition Database. Version1. World Agroforestry, Nairobi, Kenya

Table 23.4 Major Agroforestry Species Databases*

Global databases:
Ecocrop: World Economic Plants in the Germplasm Resources Information Network
Selection of Forages for the Tropics
Global Species Matrix
Tropical Forestry Handbook's most frequently used species for plantations in the tropics
Agroforestry Database
USDA Food Composition Databases
Wood Database
FAO Crop statistics
Regional databases:
Plant Resources of Tropical Africa
Useful Tree Species for Africa
Useful Tree Species for India
Árboles de Centroamérica
MAPFORGEN Atlas para la conservación de los recursos genéticos forestales
Especies para restauración
Species Profiles for Pacific Island Agroforestry
Plant Resources of South-East Asia online database
Useful Tree Species for South-East Asia
Attribute databases:
African Orphan Crops Consortium
CABI Invasive Species Compendium
Species with sequenced genome
Global Invasive Species Database
OECD Approved Basic Forest Material
Plants For A Future
Priority species for the State of World's Forest Genetic Resources
Wood density database
Global Agroecological Zones

More details on global and regional databases are available from ICRAF's Agroforestry Species Switchboard. http://www.worldagroforestry.org/products/switchboard
*Source: Kindt et al. (2020)

23.4 Indirect Role of Agroforestry in Food Security

In addition to the direct contribution of agroforestry systems to food and nutritional security, millions of smallholder farmers in the tropics are indirectly benefitted and supported by these multifunctional systems through the effect of the various ecosystem services provided by them. The status of our understanding of the important role of such ecosystem services has been presented in detail in the previous chapters (Chapters 16 through 22).

A related factor is the cash income generation from the sale of tree products and the associated enhanced purchasing power of the households. Expenditure analysis shows, however, that as the household incomes increase, the purchase of fruits increases, meaning that as incomes grow in the region due to economic development, domestic markets for fruits also grow. If production and delivery to consumers can be made more efficient, the potential for farmers to boost their incomes by meeting this increased demand is high. This may have a pronounced gender dimension too. Women farmers, in particular, could benefit since the harvesting and processing of fruits are often seen as their, rather than men's, activities. Such incomes the women receive are more likely to be used to purchase other foods for household consumption than incomes received by men, so families' diets should improve. As fruit production becomes more commercially profitable, however, businesses may be taken over by men.

Agroforestry systems may enhance food security in various indirect ways. As described in Chapter 20, the tree-based systems, compared to monocultural production systems are more resilient and have higher climate-change mitigation and adaption potential, and can better withstand the impacts of changing global climate and adverse biotic and abiotic factors such as pest/disease epidemics. Another significant aspect of food security is food quality. The diversity of food products and the resulting nutritional balance offered by organically produced fruits and other tree products weigh heavily in the food security equation. The year-round availability of different types of tree and crop products that is a characteristic feature of homegardens and other integrated production systems is yet another factor contributing to enhanced food security through agroforestry systems. The value of such intangible benefits, although well appreciated have unfortunately been not adequately quantified and therefore not recognized.

23.5 The Way Forward

Food security is an extremely important global developmental issue. The success in attaining tangible results in food security depends on the level of commitment of world leaders in formulating and implementing coordinated policy agendas and action plans involving member countries of various international organizations and experts of various disciplinary backgrounds. Several experts have articulated that agroforestry provides a pathway out of poverty because the combination of increased crop yields, low cost, and additional tree-based farm products can significantly increase net farm income (Miller et al. 2017; Reyes et al. 2005; Waldron et al. 2012). Leakey (2020) suggests that diversification and rehabilitation of degraded farmland with species producing highly nutritious and marketable traditional foods will improve food production by conventional staple food crops and create new local business opportunities and enhance social well-being. On-farm trees also generate considerable fuelwood, reducing the need to cut down natural forests and saving smallholder family members (particularly women) the drudgery of trekking progressively increasing distances in search of fast diminishing lots of firewood (Kiptot et al. 2014; Sharma et al. 2016; Thorlakson and Neufeldt 2012). Zomer et al. (2016) estimated that globally 46% of all farmland already has more than 10% tree cover, indicating the increasing realization of the benefits of maintaining and/or introducing trees to land (Garrity et al. 2010). Thus, agroforestry techniques are likely to be suitable across a large proportion of global farmland.

Ideally, each land-management strategy should be implemented where it is most appropriate in a multigoal framework. Many studies, however, have shown how conventional approaches still dominate (Pingali et al. 2016), whereas agroforestry and similar non-mainstream approaches are under-implemented (Franzel et al. 2004; Pretty et al. 2003). It defies logic as to why a land-management option such as agroforestry remains sidelined despite its long tradition of delivering food security without compromising soils, biodiversity and ecosystem services, climate, and social capital. The only plausible reason seems to be that achieving maximum yields of preferred commodities has been an economic goal, and conventional agriculture has been developed since World War II with all the needed accompaniments in infrastructure and research to fulfill that goal. The incremental yield gains from conventional agriculture, however, are gradually slowing down compared with earlier stages of development (IAASTD 2013) and the massive investments in reversing the poor environmental record of monoculture agriculture had only limited success (Kleijn et al. 2006; Monke and Johnson 2010). Investments in agroecological systems have so far been of a much smaller order of magnitude (DeLonge et al. 2016) but results of the efforts so far suggest that greater investments in less-developed approaches such as agroforestry could produce much more attractive results in enhancing productivity while maintaining environmental integrity. An opportunity has been offered for seriously considering the less-mainstream techniques such as agroforestry, which needs new investments in research and institutional changes, besides policy interventions, to significantly enhance global goals on food security, social well-being, and environmental integrity, as envisaged under the SDGs.

Annexure I

U. N. Sustainable Development Goals (2015) (https://www.un.org/sustainabledevelopment/sustainable-development-goals)

Goal 1. No Poverty: End poverty in all its forms everywhere.
Goal 2. Zero Hunger: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
Goal 3. Good health and Well-Being: Ensure healthy lives and promote well-being for all at all ages.
Goal 4. Quality Education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5. Gender Equality: Achieve gender equality and empower all women and girls.
Goal 6. Clean Water and Sanitation: Ensure availability and sustainable management of water and sanitation for all.
Goal 7. Affordable and Clean Energy: Ensure access to affordable, reliable, sustainable and modern energy for all.
Goal 8. Decent Work and Economic Growth: Promote sustained, inclusive and sustainable. economic growth, full and productive employment and decent work for all.
Goal 9. Industry, Innovation, and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
Goal 10. Reduced Inequalities: Reduce income inequality within and among countries.
Goal 11. Sustainable Cities and Communities: Make cities and human settlements inclusive, safe, resilient, and sustainable.
Goal 12. Responsible Consumption and production: Ensure sustainable consumption and production patterns.
Goal 13. Climate action: Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy.
Goal 14. Life Below Water: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Goal 15. Life on Land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
Goal 16. Peace, Justice, and Strong Institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
Goal 17. Partnerships for the goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development**.**

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Agroforestry and Land Management in the Future

24

Contents

Abstract

Since its modest beginning in the late 1970s, agroforestry has become widely recognized and accepted as a sustainable approach to land management the world over. Although the international investments in agroforestry research and development have been comparatively meager, those investments have paid off extremely well. The role and potential of agroforestry have been recognized as an alternative or a complement to the segregated approach to agricultural simplification that has been the dominant paradigm of the modern era. Recent studies and analyses have shown that as a land management system, agroforestry has the potential for achieving nine out of the 17 UN Sustainable Development Goals. It has been well recognized that scientific knowledge is only one aspect of accomplishing the complex task of sustainable development. Time and again, it has become abundantly clear that it is not the lack of scientific knowledge that hinders progress. The gap between what we already know in agroforestry and the extent to which that knowledge is applied is widening. Therefore, a two-pronged approach is needed in agroforestry research and development: intensify research in key areas with potentially wide applicability of the results, and promote technology transfer for which the support of an enabling policy framework is critical. At a time when the world seems to be trying to solve its agricultural and other land-management problems through robotics and genetic engineering, we should be vigilant not to lose track and be left out of the opportunities to employ modern technological tools in agroforestry research and development.

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_24

24.1 Introduction

The circumstances and developments that led to the establishment of ICRAF for promoting research in agroforestry in the late 1970s are chronicled in the first chapter of the book. The activity that started as a relatively small project resulted in the recognition and revival of a form of land-management that had been practiced for long but had been ignored and bypassed in the efforts to modernize agricultural and forestry production technologies during the second half of the 20th century. With the new name agroforestry, the practice has become widely recognized and accepted as a sustainable approach to land management the world over during the past four decades. This remarkable development was initiated by the Canadian government agency IDRC (International Development Research Centre) with the appointment of a small team to study and suggest ways for addressing the problem of tropical deforestation and its devastating consequences. The study recognized that the primary reason for the wanton destruction of tropical forests was the ever-increasing need for additional land to cultivate staple food crops by the landless poor farmers, whose population was increasing at an alarming rate around the tropics. The team noted that although cultivating trees and crops together was an age-old practice in most parts of the world, that traditional practice was overlooked in the push for promoting commodity-specific activities with heavy investments in research to support agriculture and forestry during the 1960s and 1970s (Bene et al. 1977). The team recommended the initiation of an international effort to support research in agroforestry, a term that was coined to facilitate the "remarriage of trees and crops" (Chapter 1).

The major force behind initiating and pushing that effort forward, despite formidable difficulties, was the undaunted determination of the indefatigable Canadian forester of Hungarian origin John G. Bene, the project's leader, and the excellent support he received from outstanding professionals such as Dr. Kenneth King, the head of forestry at FAO at that time. Bene was deeply concerned about the rampant deforestation that was happening in the tropics. His words at one of the meetings of a committee that had been assembled in 1977 (Figure 1.9) to help move forward with the action plans still ring in the ears of this author (PKR N): when the bureaucratic procedures and hurdles were being discussed, the normally soft-spoken Bene was visibly upset and lamented: "every day this process is delayed, a thousand hectares of tropical forest will go up in flames."

24.2 The Past

If and to what extent the initiation of agroforestry research with international support has helped to reduce tropical deforestation are questions that cannot be answered convincingly. According to the latest SOFO (State of the World's Forests) report (FAO 2020), not only has deforestation been not controlled, but its pace has indeed increased in the late 2010s in some places such as the Amazon region of Brazil, home of the world's most extensive tropical forests (see Chapter 1, Figure 1.8). But that does not give a clear indication of the impact agroforestry has had on slowing down tropical deforestation. Two facts, however, are irrefutable: 1. the international investments in agroforestry research and development during the past four decades have been comparatively meager considering the number of people impacted by the practice or the extent of area involved, and 2. the investments, however meager, have paid off extremely well. The best testimony for the latter point is the high scientific standards of the mostly application-oriented research presented in more than 700 presentations from 100+ countries at the Fourth World Congress of Agroforestry (https://agroforestry2019.cirad.fr/), held at Montpellier, France, in May 2019 (see the Book of Abstracts: https://www.alphavisa.com/agroforestry/2019/documents/Agroforestry2019-Book-of-Abstract-v1.pdf).

The scientific advances made in the subject summarized in the previous chapters of this book are indeed credible, numerous, and impactful. Agroforestry-focused publications are featured regularly in most thematic scientific journals related to land-use disciplines. Several such indicators are available that can attest to the enormous progress that agroforestry has made since its modest beginnings. The untested seed of agroforestry that was planted more than four decades ago in an infertile landscape in a difficult environment without an assured supply of water, nutrients, and other growth factors has not only germinated and weathered the hazards and threats during its juvenile phase, but has grown into a full-grown tree offering enormous benefits and services to the humans, animals, and the environment on a sustained basis, and has earned a deservingly prominent place in the landscape of land-use disciplines.

24.3 The Present

It is interesting to revisit some of the early expectations about agroforestry such as a visualization of the "state of agroforestry systems in the 1990s and beyond." As the keynote speaker to the well-attended international conference on *Agroforestry: Principles and Practice* held at Edinburgh, UK, in July 1989 (considered to be the forerunner to the series of World Congresses of Agroforestry held once every five years since 2004), Nair (1991) visualized some global scenarios of the state of agroforestry systems in the1990s and beyond that included:

– Serpentine hedgerows of fast-growing multipurpose trees and shrubs offering renewed hope to the poor farmers of Haiti and other impoverished countries to raise food crops in the sloping lands and denuded hills,
– Coffee grown on small farms under shade trees in the highlands of Central America and elsewhere, and cacao grown similarly under widely spaced stands of commercial tree crops in the humid lowlands of Brazil, and South & Southeast Asia,
– Homegardens and other multispecies, multistoried plant associations of South and Southeast Asia and other regions that provide valuable commodities of high economic values,
– Nitrogen-fixing shrubs and short-duration trees planted simultaneously or sequentially with food crops to regenerate the soil's productivity and improve crop yields,
– Fast-growing firewood species grown along plot boundaries providing fuel for cooking and fodder for domestic animals, as well as reducing desertification hazards in semiarid lands in sub-Saharan Africa and elsewhere,
– Block planting of soil-ameliorating trees on salt-affected soils in vast areas extending from northern India westwards to Central Asia, as well as in Australia and other places,
– Improved fodder trees and regulated cattle stocking in silvopastoral areas of Latin America, Africa, and elsewhere,
– Tree-lined embankments, shelterbelts, and catchment areas for arresting wind erosion, stabilizing embankments, and providing fodder and fuelwood in hilly regions,
– Cattle grazing on grasses and other fodder under widely spaced rows of commercial tree plantations around the world,
– Extensive stands of black walnut (Juglans spp.), honey locust (*Gleditsia triacanthos*), and other fruit- and timber trees interplanted with crops in North America and Europe,
– And so on, and on, . . .

These and many more manifestations and examples of agroforestry are, indeed, practiced today throughout the world as described in various chapters of this book, especially in Section II (Chapters 6 through 11). This does not mean that agroforestry is flourishing at its peak everywhere. Certainly not! This description only shows that agroforestry has come a long way. Perhaps what the list does not reveal is more important and exhaustive than what it does: the level of intensity at which agroforestry is practiced, the extent of area covered and benefits accrued, and new directions that agroforestry has taken cannot be surmised from such a rather superficial and promotional-type of listing.

Among the new directions in which agroforestry has made some headway during the past three decades since Nair's (1991) visualization referred to above, the most notable is the role and importance of agroforestry in climate change mitigation and adaptation and provision of other ecosystem services. Aside from the COVID-19 that has ravaged and brought untold havoc throughout the world in 2020, climate change is portrayed as the most consequential issue the world is grappling with. The underlying scientific foundations of the perceived prominent role of agroforestry systems in carbon sequestration in soils and aboveground biomass as a strategy for addressing climate change are elucidated based on an extensive review in Chapter 20. It articulates that the relatively higher efficiency of trees and other perennial species that are an integral part of agroforestry systems would help store atmospheric CO_2 in the biomass and soils. The hypothesis that agroforestry systems, compared with treeless agricultural systems, would lead to higher rates of carbon sequestration, i.e., removal of carbon from the atmosphere and its storage in soils and plants for longer periods, has been convincingly proven by research results from different ecological regions and a wide range of agroforestry systems around the world.

Equally impressive are the developments during the past few years on the exploitation of other ecosystem services provided by agroforestry systems. Right from the early days of agroforestry development, the role and potential of agroforestry had been recognized as an alternative or complement to the segregated approach to agricultural simplification that has been the dominant paradigm of modern agriculture, where ecological functions are substituted by technical means and external inputs. Kenneth King, one of the pioneers of the "agroforestry movement," articulated in his keynote address to the eighth World Forestry Congress, Jakarta, Indonesia, in 1978 that "the existence of large numbers of people, as well as the greater proportion of the land in the fragile ecosystems of the developing world, means that ways must be devised to assist in increasing the productivity of these ecosystems while at the same time arresting the progression of continuing land degradation." He proposed that "agroforestry is such a system of land management that seems to be suitable for such ecologically brittle areas as it combines the protective characteristics of forestry with the productive attributes of both forestry and agriculture" (King 1979). The two major ecosystem services of agroforestry systems that received early recognition since the early 1980s were the exploitation of nitrogen-fixing ability of tropical leguminous trees and shrubs (nitrogen-fixing trees, NFTs) for enhancing nitrogen supply to crops grown in conjunction with such NFTs as described in Chapter 17, and the incorporation of trees and shrubs in arresting soil erosion and land degradation as detailed in Chapter 18. Subsequently, with the activities surrounding the Millennium Ecosystem Assessment described in Chapter 19, other major ecosystem services of agroforestry under all the four major categories (Provisioning, Regulating, Cultural, and Supporting: see Table 19.1) have also received increasing attention, notably in biodiversity conservation (Chapter 21).

24.4 The Future

As we wade through the fifth decade of agroforestry development, we need to be cognizant of the unexpected and disastrous impacts of the global pandemic COVID-19 in 2020 that have compelled us to retool our approaches to all futuristic plans and aspirations. Many institutions have dug into the causes and consequences of the pandemic assessing what lessons can be learned from this tragedy. The IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) is possibly one of the first in this effort. The Report of an IPBES Workshop organized in cooperation with several other such organizations in July 2020 concluded that "The underlying causes of pandemics are the same global environmental changes that drive biodiversity loss and climate change. These include land-use change, agricultural expansion, and intensification, and wildlife trade and consumption." The Report calls for "transformative changes, using the evidence from science to re-assess the relationship between people and nature and reduce global environmental changes that are caused by unsustainable consumption, and which drive biodiversity loss, climate change, and pandemic emergence" (https://ipbes.net/pandemics). These conclusions and recommendations, despite the lack of clarity in the Report on the reasons and evidence upon which they were drawn, are in total agreement with the strategy and directions of the UN SDGs (Sustainable Development Goals), the internationally accepted global development agenda (Appendix I; Chapter 13). The role and importance of agroforestry in attaining the SDGs as explained in Chapter 23 are thus fully applicable to the IPBES recommendations as well.

Such global development agendas often attract criticisms from many quarters as being too general and ineffective. Both the SDGs and its precursor, the MDGs (Millennium Development Goals: Garrity 2004) are no exception. They have been criticized for attempting to include everything important and desirable to the society, or for including too many players and/or not giving deserving attention to some others, and so on (Holden et al. 2017). Nevertheless, as van Noordwijk et al. (2019) put it, these global efforts are the most legitimate and feasible attempts at governing a highly heterogeneous entity like the world. From the agroforestry perspective, it is better to join the effort than be left out, especially when the opportunities for demonstrating the merit and importance of agroforestry are abundant as articulated by Nair and Garrity (2012).

Recent studies and analyses (e.g., Agroforestry Network 2018; van Noordwijk et al. 2019) have shown that as a land management system, agroforestry has the potential for achieving nine out of the 17 sustainable development goals (SDG) including poverty reduction (SDG 1) and hunger alleviation (SDG 2), climate change mitigation (SDG 13), biodiversity conservation and sustainable land management (SDG 15). These claims are amply supported by the irrefutable scientific evidence that has been accumulated through four decades of scientific efforts and developments in agroforestry that are summarized in this book, including:

- Food security (Chapter 23)
- Climate-change mitigation through carbon sequestration (Chapter 20)
- Soil health (Chapter 16)
- Biodiversity conservation (Chapter 17)
- Soil conservation and land-degradation control (Chapter 18)
- Ecosystem sustainability (Chapters 19, 21, and 22)

The relevance of agroforestry systems in attaining the SDGs and pandemic preparedness is, thus, abundantly clear. It has been well recognized, however, that scientific knowledge is only one aspect of accomplishing the complex task of sustainable development. Time and again, it has become abundantly clear that it is not the lack of scientific knowledge that hinders progress, except, maybe, in totally unforeseen calamities such as the COVID-19 pandemic. As Nair and Garrity (2012) emphasized, the gap between what we already know in agroforestry and the extent to which that knowledge is applied – i.e., the knowledge that is transferred to the practitioners – is widening. While we endeavor to intensify technology transfer efforts, we also need to continuously replenish and update the stockpile of our technical knowledge. We need a two-pronged approach in agroforestry research and development: intensify research in key areas with potentially wide applicability of the results, and intensify efforts in technology transfer, which itself will need research support to the science of scaling-up to develop new and innovative approaches. Enabling policies and appropriate research are the key in both development and transfer and transfer of technology. At a time when the world seems to be moving toward trying to solve its agricultural and other land-management problems through robotics and genetic engineering than through agroecological approaches, we need to be careful that agroforestry and other similar waves of enthusiasm embodied in novel terms such as regenerative agriculture – even if they are new names for an old set of ideas – do not miss the boat.

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Acronyms and Abbreviations[1]

AGFORWARD	AGroFORestry that Will Advance Rural Development
CAP	Common Agriculture Policy of the European Union
CARE	Cooperative for American Relief Everywhere (New York, USA)
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza (Tropical Agricultural Research and Education Centre, Turrialba, Costa Rica)
CAZRI	Central Arid Zone Research Institute (Jodhpur, India)
CBD	Convention on Biological Diversity
CGIAR	Consultative Group on International Agricultural Research (Washington, D.C., USA)
CITES	the Convention on International Trade in Endangered Species of Wild Fauna and Flora
CPCRI	Central Plantation Crops Research Institute (Kasaragod, India)
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Enterprise)
EURAF	European Agroforestry Federation
FAO	Food and Agricultural Organization of the United Nations (Rome, Italy)
GLASOD	Global Assessment of Human-Induced Soil Degradation
IARC	International Agricultural Research Center
ICAR	Indian Council of Agricultural Research (New Delhi, India)
ICFRE	Indian Council of Forestry Research and Education (Dehradun, India)
ICRAF	International Centre for Research in Agroforestry (Nairobi, Kenya)
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics (Hyderabad, India)
IDRC	International Development Research Centre (Ottawa, Canada)

[1] Institutions/organizations only.

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IFPRI	International Food Policy Research Institute (Washington, DC, USA)
IITA	International Institute of Tropical Agriculture (Ibadan, Nigeria)
ILCA	International Livestock Center for Africa (Addis Ababa, Ethiopia)
INRA	Institut national de la recherche agronomique (The national agricultural research institute, France)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature (Gland, Switzerland)
NAS	National Academy of Sciences (Washington, D.C., USA)
NASA	National Aeronautical and Space Administration, USA
NFTA	Nitrogen Fixing Tree Association (Paia, Hawaii, USA)
NORAD	Norwegian Agency for Development Cooperation
NRCS	Natural Resources Conservation Service (USDA), previously Soil Conservation Service (SCS)
RRIM	Rubber Research Institute of Malaysia
SIDA	Swedish International Development Agency
SSSA	Soil Science Society of America
TSBF	Tropical Soil Biology and Fertility program (Nairobi, Kenya)
TVA	Tennessee Valley Authority (Knoxville, USA)
UNCCD	United Nations Convention to Combat Desertification
UNCED	UN Conference on Environment and Development
UNEP	United Nations Environment Program (Nairobi, Kenya)
UNESCO	United Nations Educational, Scientific, and Cultural Organization (Paris, France)
UNFCCC	United Nations Framework Convention on Climate Change
UNU	United Nations University (Tokyo, Japan)
USAID	United States Agency for International Development (Washington, D.C., USA)
USDA	United States Department of Agriculture (Washington, D.C., USA)
WMO	World Meteorological Organization (Geneva, Switzerland)
WRI	World Resources Institute (Washington, D.C., USA)

Glossary

$\delta^{15}N$	Delta-N-15 is a measure of the ratio of the two stable isotopes of nitrogen, $^{15}N:^{14}N$
Acetylene reduction assay (ARA)	A diagnostic tool to evaluate the activity of the nitrogenase enzyme system
Acid soil	A soil with a pH value < 7.0. Usually applied to surface layer or root zone, but may be used to characterize any horizon.
Actinomycetes	A group of organisms intermediate between the bacteria and the true fungi that usually produce a characteristic branched mycelium.
Actinorhizal plants	A group of non-leguminous plants that develop an endosymbiotic association with the nitrogen-fixing soil actinomycete, *Frankia*.
Additive series intercropping	An intercropping system in which the plant population of the main crop is kept constant into which an intercrop is introduced by adjusting or changing the crop geometry.

(continued)

Aerobic respiration	Process of the breakdown (oxidation) of the sugars formed during photosynthesis to yield the energy required for plant growth.
Afforestation	The act or process of establishing a forest especially on land not previously forested.
AFOLU	Agriculture, Forestry, and Other Land-Use activities.
Agricultural intensification	An increase in agricultural production per unit of inputs (which may be labor, land, time, fertilizer, seed, feed or cash).
Agrisilviculture	A form of agroforestry consisting of tree (woody perennial) and crop components.
Agrobiodiversity (Farmland Biodiversity)	The variety and variability of animals, plants, and microorganisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry, and fisheries.

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Agrodeforestation	Loss of tree cover from the agricultural landscape.
Agroecosystem	A spatially and functionally coherent unit of agricultural activity, and includes the living and nonliving components involved in that unit as well as their interactions.
Agroforestry	Growing trees (woody perennials), crops, and/or animals in interacting combinations.
Agroforestry parklands	Areas where scattered multipurpose trees occur on farmlands as a result of farmer selection and protection; widespread in the tropics.
Agroforestry practices	A distinctive arrangement of components in space and time and the actual application or use of an idea, belief, or method.
Agroforestry systems	A specific local example of a practice, characterized by environment, plant species and their arrangement, and management
Agroforestry technology	Innovation or improvement of agroforestry systems, usually through scientific intervention, to either modify an existing system or practice or develop a new one.
Agrosilvopasture	A form of agroforestry consisting of tree (woody perennial), crop and pasture/animal components.
Alkali soil or sodic soils	A soil that contains sufficient alkali (sodium) to interfere with the growth of most crop plants (The term is scientifically obsolete, but is still used and understood widely).

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Allelopathy	Production of chemicals by plants that inhibit the growth of companion crops.
Alley cropping	An agroforestry practice of growing an arable crop between rows of trees or perennial shrubs. Two variants: tropical and temperate forms (see Chapters 6 and 10 respectively).
Alluvial soil	A soil developing from recently deposited alluvium and exhibiting essentially no horizon development or modification of the recently deposited materials (The term is scientifically obsolete, but is still used).
Alpha diversity	The diversity of species within an ecological community, or the species richness of standard site samples.
Anion exchange capacity (AEC)	The ability of a soil to adsorb or release anions.
Annual plant	A plant that grows for only one season (or year) before dying, in contrast to a perennial, which grows for more than one season.
Area-time-equivalency-ratio (ATER)	An adaptation of Land Equivalent Ratio that takes account of land left unused after harvesting the shorter duration crop component.
Arid climate	Climate in regions that lack sufficient moisture for crop production without irrigation. In cool regions, annual precipitation is usually less than 25 cm. Natural vegetation is desert shrubs.

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Available nutrient	That portion of any element or compound in the soil that can readily be absorbed and assimilated by growing plants ("Available" should not be confused with "exchangeable").
Avenue cropping	A form of hedgerow intercropping (see hedgerow intercropping).
Base saturation percentage	The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen and aluminum; expressed as a percentage of the total cation exchange capacity.
Bench terrace (soil)	An embankment constructed across sloping fields with a steep drop on the downslope side.
Beta diversity	The extent of species replacement or biotic change along environmental gradients.
Biennial plant	A plant that completes its life cycle in two years, producing leaves and roots the first year, and stems and flowers/seeds in the second year.
Biochar	A carbon-rich organic material produced by pyrolysis of biomass such as wood, manure, or crop residues and byproducts.
Biocultural diversity	The total variety exhibited by the world's natural and cultural systems, explicitly considers the idea that culture and nature mutually constitute and incorporates ethno-biodiversity.
Biodiversity	The variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part; includes diversity within and between species and of ecosystems.
Biodiversity coldspots	Areas with considerable biological diversity but not counted as biodiversity hotspots.
Biodiversity hotspots	Regions of the world with unusually high concentrations of endemic species that suffer severe habitat destruction.
Biodrainage or biological drainage	The use of vegetation to manage water fluxes in the landscape (to remove excess soil water through evapotranspiration).
Biomass	The weight of material produced by a living organism or collection of organisms. The term is usually applied to plants to include the entire plant, or it may be qualified to include only certain parts of the plant, e.g., aboveground and belowground.
Browse (noun)	The buds, shoots, leaves, and flowers of woody plants, which are eaten by livestock or wild animals; the verb form means consuming the parts.
Bulk density, soil	The mass of dry soil per unit of bulk volume, including the air space. The bulk volume is determined before drying to constant weight at 105 °C.
Bund	A ridge of earth placed in a line to control water runoff

(continued)

	and soil erosion, demarcate plot boundary, or other uses.
Bush	1. Small woody plant (see shrub); 2. Uncleared, wild landscape with scattered vegetation.
Bush-fallow system	The shifting cultivation practice that is common in Sub-Saharan Africa.
C_3 plants	Species with the photosynthetic pathway in which the first product of CO_2 fixation is a 3-carbon molecule (3-phosphoglyceric acid) (see Chapter 12).
C_4 plants	Species that have 4-C acids (malate and aspartate) as primary CO_2 fixation products (see Chapter 12).
Caatinga	Biome of Northeast Brazil with some of the most complex bio-climatological features.
CAM (Crassulacean Acid Metabolism) plants	Species with stomata that open primarily at night, and organic acids, especially malic, as the primary CO_2 fixation products (see Chapter 12).
Canopy drip	The proportion of the precipitation intercepted by a plant, which is redirected to the edge of its canopy from where it falls off.
Carbon farming	Farming methods organized around carbon sequestration in soils and plants.
Carbon sequestration (Biological)	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 long-lived pools.

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Carbon/nitrogen ratio	The ratio of the weight of organic carbon (C) to the weight of total nitrogen (N) in a soil or organic material.
Cation	A positively charged ion
Cation exchange (soil)	The interchange between a cation in solution and another cation on the surface of any surface-active material such as clay or organic matter.
Cation exchange capacity (CEC)	The sum of exchangeable cations that a soil can absorb. Sometimes called "total exchange capacity," "base exchange capacity," or "cation adsorption capacity." Expressed in centimoles per kilogram (cmol kg^{-1}) of soil (or of other adsorbing material such as clay).
Cereal	A grass that is grown primarily for its seed that is used for feed or food.
Cerrado	Brazilian savanna occurring mainly in the central Brazilian states.
Chagga system	Homegardens on the slopes of Mt. Kilimanjaro, especially on the upper southern slopes nurtured by the *Chagga* tribe.
Chloroplast	A type of plastid, a double membrane-bound, organelle peculiar to higher plant cells, in which the photosynthetic apparatus is localized.
Cinderella agroforestry systems	The underexploited, location-specific and "forgotten" agroforestry systems, which provide a myriad of products and services.

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Climate change	Any long-term change in Earth's climate, or in the climate of a region.
Climate change adaptation	Initiatives and actions to decrease the susceptibility of natural and managed systems to climate change.
Climate change mitigation	The technological change and substitution that decrease GHG emissions through avoiding emissions and sequestering GHGs.
Climate smart agriculture (CSA)	An approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate.
Climate smart soils	Refers to the implementation of soil-based greenhouse gas mitigation activities, and adaptation to climate change through soil management
Closed nutrient cycling systems	With relatively little loss or gain of the actively cycling nutrients and high rates of nutrient turnover within the system.
Clump (plants)	A close grouping of stems of trees, bushes, or grasses.
CO_2 compensation point	The CO_2 concentration at which photosynthetic fixation just balances respiratory and photorespiratory loss: 50–100 ppm for C_3 and 0–5 for C_4 plants.
Coconut-based farming system, CBFS	Multi-species, multi-strata tree-, shrub-, field-crop and livestock systems integrated with coconuts.

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Community forestry	A form of social forestry, where tree planting is undertaken by a community on common or communal lands.
Competition	An interaction where the net effects are negative for one or both species in a mixed species system.
Conservation agriculture (CA)	A sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region for optimizing yields.
Contour	An imaginary line connecting points of equal elevation on the surface of the soil. A contour terrace is laid out on a sloping soil at right angles to the direction of the slope and nearly level throughout its course.
Coppicing	Cutting certain tree species close to ground level to produce new shoots from the stump. Also occurs naturally in some species if the trees are damaged.
Cover crop	A close-growing crop grown for protecting soil between periods of regular cropping or between trees and vines in orchards and plantations.
Crop growth rate	The gain in weight of a plant on a unit of area in a unit of time.
Cropping pattern	The yearly sequence and spatial arrangement of crops or of crops and fallow on a given area.

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Cropping system	The cropping patterns used on a farm and their interaction with farm resources, other farm enterprises, and available technology
Crown	The canopy or top of a tree or other woody plant that carries its main branches and leaves at the top of the stem.
Cultivation factor, R	Inverse of the land-use factor (L), which is the ratio of the sum of the length of cropping and fallow periods to that of the cropping period.
Cut-and-carry	Fodder or other plant products, which are harvested and carried to a different location, usually to be fed to the animals in pens or sheds.
Cutting (plant)	A piece of a branch or root cut from a living plant for propagating the plant; genetically identical to the original parent (a clone).
Deciduous plant	A plant that sheds all or most of its leaves every year at a certain season. The opposite of evergreen.
Decomposition (litter)	The conversion of litter to soil humus.
Deforestation	Human-induced conversion of forested land to non-forested land.
Degraded lands	Land that has been seriously eroded or overgrazed, or is highly saline or alkaline.
Dehesa	The centuries-old silvopasture system of the Mediterranean region of Europe, especially Spain and Portugal (Chapter 10).

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Denitrification	The biochemical reduction of nitrate or nitrite to gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen.
Detritus (in ecology)	Matter composed of leaves and other plant parts, animal remains, waste products, and other organic debris that falls onto the soil or into bodies of water from surrounding terrestrial communities.
Desertification	Land degradation in the arid, semiarid, and subhumid regions of the world.
Detritus	Discarded, dead, or decomposing bodies or fragments of organisms.
Dioecious	Having the flowers bearing the stamens and those bearing the pistils produced on separate plants.
Direct seeding	Sowing seeds directly where they are to develop into mature plants.
Discounting	Determining the present worth of a future amount of money.
Domestication	Plant domestication is the process whereby wild plants have been evolved into crop plants through artificial selection.
Drought	The absence of precipitation for a period long enough to cause depletion of soil moisture and damage to plants.
Drought tolerance	The capacity of plants to survive drought; specifically, adaptations that enhance their power to withstand drought-induced stress.

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Ecological resilience	The capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly.
Ecosystem	All the plants and animals in a specified area and their physical environment, including the interactions between or among them.
Ecosystem diversity or ecological diversity	The variety and variability of communities or habitats that exist in a given geographical area.
Ecosystem services (ES)	The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth.
Ecotourism	Responsible travel to natural areas that conserves the environment and sustains the well-being of the local people.
Ectotrophic mycorrhiza (ectomycorrhiza)	A symbiotic association of the fungi and the roots of certain plants, in which the fungal hyphae form a compact mantle on the surface of the roots and extend into the surrounding soil and inward between cortical cells, but not into these cells. Associated primarily with certain trees.
Endotrophic mycorrhiza (endomycorrhiza)	A symbiotic association of the fungi and roots of a variety of plants in which the fungal hyphae penetrate directly into the root hairs, other epidermal cells, and occasionally into the cortical cells. A common example is the vesicular arbuscular mycorrhiza (VAM).
Enrichment planting	Planting with desirable tree and understory species.
Equitability or Evenness	The relative abundance of different types of items (species) in an area.
Erosion	(1) The wearing away of the land surface by running water, wind, ice, or other geological agents. (2) Detachment and movement of soil or rock by water, wind, ice, or gravity. The following terms are used to describe different types of water erosion.
	accelerated erosion: Erosion much more rapid than normal, natural, geological erosion; primarily caused by activities of the humans, and sometimes animals.
	gully erosion: The removal of soil by water in deep, narrow channels.

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	natural erosion (geological)	Wearing away of the Earth's surface by water, ice, or other natural agents under natural conditions.
	rill erosion	An erosion process in which numerous small channels of only several centimeters in depth are formed
	sheet erosion	The removal of a uniform layer of soil from the land surface by runoff water.
	splash erosion	The spattering of small soil particles by the impact of raindrops on wet soils. The loosened particles may be subsequently removed by surface runoff.
Ethnobiodiversity	The interactions between the genetic diversity of wild and domesticated organisms and that of needs, tastes, and preferences of domesticators.	

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Ethnoforestry	Traditional ecological knowledge on forests.
Eutrophication	Nutrient enrichment of an ecosystem, generally resulting in increased primary production and reduced biodiversity. In lakes, eutrophication leads to algal blooms, reduced water clarity, and periodic fish mortality.
Evaporation	Loss of moisture from surfaces other than plants.
Evapotranspiration	The combined loss of water from a given area during a specified period, by evaporation from the soil surface and by transpiration from plants.
Evergreen	Plants that retain their leaves and remain green throughout the year; opposite of deciduous.
Exotic	A plant or animal species which has been introduced outside its natural range; opposite of indigenous.
Extensive	Land use or management spread over a large area where land is plentiful (at least for those who control it); opposite of intensive.
Fallow	Land resting from cropping, which may be grazed or left unused, often colonized by natural vegetation.
Family (plant)	A taxonomic category between order and genus. Plants or animals in the same family share some common characteristics.

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Farm enterprise	An individual crop or animal production function within a farming system, which is the smallest unit for which resource-use and cost-return analyses are normally carried out.
Farm forestry	Commercial tree planting on farmers' private lands as woodlots, shelterbelts, scattered trees, or boundary rows.
Farming system	All the elements of a farm which interact as a system, including people, crops, livestock, other vegetation, wildlife, the environment, and the social, economic, and ecological interactions between/among them.
Fodder	Parts of plants that are eaten by domestic animals. These may include leaves, stems, fruit, pods, flowers, pollen, or nectar.
Fodder banks	Designated, often enclosed, areas where fodder trees and shrubs – especially leguminous ones – are grown intensively for a steady supply of fodder, especially during the dry season.
Foliage	The mass of leaves of a plant or tree, or leaves on the stems or branches on which they are growing.
Food security	Food security exists "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life" (The World Food Summit, 1996).
Forage	Vegetative material in a fresh, dried, or ensiled state which is fed to livestock (hay, pasture, silage).

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Forest	A minimum area of land of 0.05 – 1.0 ha with tree crown cover (or equivalent stocking level) of more than 10–30% with trees having the potential to reach a minimum height of 2–5 m at maturity *in situ*.
Forest farming	Cultivation or management of understory crops within an established or developing forest (Chapter 10).
Forest gardens	Patches of domesticated forests around human settlements with one or a few useful species analogous to tropical homegardens; tree gardens are usually away from houses. Other similar terms include multistory tree gardens and mixed tree gardens. *Talun-Kebun* and *Pekarangan* are used for various types of homegarden systems of Java (Indonesia).
Four per mille (4p 1000).	An aspirational goal to increase global soil organic matter stocks by 0.4 percent per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources.
Four-side plantations	Trees around houses and along roads, canals, and villages in China.
Gamma diversity	The diversity of species across larger landscape levels.
Genetic diversity	Extent of heritable variations within a population.
Genus	A taxonomic category between family and species.

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Global warming	The increasing average global temperature since the Industrial Revolution: the average global temperature has increased by about 0.8 degrees Celsius (1.4 degrees Fahrenheit) since 1880.
Great Green Wall of China	The longest windbreak/shelterbelt project in the world designed to hold back the expansion of the Gobi Desert; also known as Three-North Shelterbelt Program.
Green manure	Green leafy material applied to the soil to improve its fertility.
Green Revolution	Food-production technologies, emphasizing the newly developed high-yielding varieties of cereal crops in sole-crop stands with heavy input of agrochemicals (fertilizers, insecticides, herbicides, etc.), mechanization and irrigation, developed during the second half of the 20th century.
Greenhouse gases (GHGs)	The gases in the atmosphere that cause an effect comparable to that in a greenhouse. The common GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).
Groundcover	Living or nonliving material which covers the soil surface.
Groundwater	Water which is underground. It may be pumped to the surface or reached by plant roots or wells or may feed into bodies of surface water.
Gully	A deep, narrow channel cut into the soil by erosion.

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Gully erosion	(See under erosion)
Hedgerow (or hedge)	A closely planted line of shrubs or small trees, often forming a boundary or fence.
Hedgerow intercropping	Also known as alley cropping: an agroforestry practice in which perennial trees or shrubs are grown simultaneously with an arable crop. The trees, managed as hedgerows, are grown in wide rows and the crop is planted in the interspace or "alley" between the tree rows.
Herbaceous	A non-woody annual plant.
Herbivore	An animal that feeds only on plants.
Homegarden	Multispecies combinations of a variety of economically useful plants including trees, shrubs, vines, and herbaceous species in small landholdings around or adjacent to the home (see Chapter 7).
Humus	Fully decomposed organic matter that is a part of the soil colloidal complex.
Improved fallow	The use of improved tree and shrub species during the fallow phase for soil fertility management and for enhancing crop production in nutrient-depleted soils. Two variants when non-coppicing tree species are used: *Sequential fallows* (the same fallow species is used in successive fallow periods) and *rotational fallows* (a fallow species used in one fallow period is replaced by another species in the subsequent fallow cycle).

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Indigenous	Native to a specific area; not introduced. Opposite of exotic.
Indigenous and local knowledge systems	Social and ecological knowledge, practices and beliefs pertaining to the relationship of living beings, including people, with one another and with their environments.
Infiltration	The downward movement of water into the soil.
Infiltration rate	A soil characteristic that refers to the maximum rate at which water can enter the soil under specified conditions.
Inoculation	The process of introducing pure or mixed cultures of microorganisms into natural or artificial culture media.
Integrated crop livestock forestry systems	An agricultural production strategy that integrates different production systems – agricultural, livestock, and forestry – within the same area.
Intensive (Land use)	Land use or management concentrated in a small area of land; opposite of extensive.
Intercropping	Growing two or more crops in the same field at the same time in a mixture.
Isotope dilution technique	An analytical technique used to determine the concentration of an element in a sample by means of a mass spectrometer.
Leaf area index (LAI)	The ratio of leaf area (one surface only) of a plant to the ground area on which it grows.

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Land degradation	Any change to the land perceived to be deleterious or undesirable.
Land degradation neutrality (LDN)	A state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems; one of the UN Sustainable Development Goals.
Land equivalent ratio (LER)	Ratio of the area needed under sole cropping to the area under intercropping, at the same management level, that is required to provide an equivalent yield (see Chapter 12).
Land-sharing vs. Land-sparing	The *land-sharing* strategy refers to the integration of agriculture and conservation within multifunctional landscapes of traditional smallholder systems. *Land-sparing* approach separates the landscapes into two or more “monofunctional” units optimized for agricultural production and biodiversity conservation.
Land use factor	Ratio of the sum of the length of cropping and fallow periods to that of the cropping period.
Land use system	The way in which land is used by a particular group of people within a specified area.
Landscape	An area of land, usually between 10 and 100 square kilometers, including

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	vegetation, built structures, and natural features, seen from a particular viewpoint. Landscape ecologists and landscape designers use this term differently from the more popular definition used in this text.
Legume inoculation	The inoculation of legume seeds with a specific culture of bacteria that multiply in the roots of a legume plant forming nodules where the bacteria fix atmospheric nitrogen for the nutrition of the plant.
Lignin	The complex organic constituent of woody fibers in plant tissue that, along with cellulose, cements the cells together and provides strength. Lignin is not easily decomposed by microbes.
Litter	From the soil fertility perspective, litter refers to the layer of organic material on the soil surface, including leaves, twigs, and flowers, freshly fallen or slightly decomposed.
Living fence	Boundary markers consisting of trees or shrubs planted on property lines that serve as poles for establishing barbed-wire fence-lines.
Long day plant	One that flowers in response to long days (daylight 11–16 hours).
Lopping	Cutting one or more branches of a standing tree or shrub.
Low Activity Clay (LAC) soils	Soils whose exchange complex are dominated by clay minerals with low cation exchange capacity

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	(CEC), such as the 1:1 layer silicates of the kaolin group and are therefore usually infertile.
Macrosymbionts	The host plant in the symbiotic N_2 fixation process whose roots get infected by soil bacteria and form structures known as nodules.
Meta-analysis	A quantitative statistical analysis of several separate but similar experiments or studies to test the pooled data for statistical significance.
Microsymbionts	The symbiotic N_2-fixing soil microorganisms (e.g., rhizobia, *Frankia*).
Mineralization	The conversion of an element from an organic form to an inorganic state during microbial decomposition.
Mixed cropping	Growing other perennials in the interspaces of perennial plantations.
Mixed farming	Cropping systems which involve the raising of crops, animals, and/or trees.
Monoculture	The repetitive growing of the same (sole) crop on the same land.
Mulch	Plant or nonliving materials used to cover the soil surface with the object of protecting the soil from the impact of rainfall, controlling weeds or moisture loss and, in some cases, fertilizing the soil.
Multifunctionality	The condition of being able to provide one or several functions in addition to its primary role.

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Multipurpose trees	Those trees and shrubs which are deliberately kept and managed for more than one preferred use, product, or service.
Multistoried (sometimes written as multistoreyed)	Relating to a vertical arrangement of plants so that they form distinct layers, from the lower (usually herbaceous) layer to the uppermost tree canopy.
Multistory tree gardens/mixed tree gardens	Mixed tree plantations consisting of conventional tree/forest species and other commercial tree crops, especially tree spices, giving the system the appearance of a managed, mixed forest.
Multistrata systems	Agroforestry systems composed of several strata of trees and tree crops.
N_2 fixation potential (NFP)	The highest N_2-fixing ability of a given species when no limiting factors are present.
Net assimilation rate	Net gain of (photosynthetic) assimilates, per unit of leaf area and time.
Net present value (NPV)	An indicator of a project's long-term value as estimated at the time of implementation; calculated over the prescribed life span of a project, based on a preselected discount rate.
Nitrogen cycle	The sequence of chemical and biological changes undergone by nitrogen as it moves from the atmosphere into water, soil, and living organisms, and is recycled upon death of the organism (plant/animal).
Nitrogen fixation	The biological conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilized in biological processes.
Non-point source pollution (NPSP)	Loading up the aquatic systems with nutrients and other chemicals from fertilizers and other agrochemicals used in intensive chemical agriculture, which causes the build-up of such pollutants at points away from where they are originally applied.
Nutrient cycling	Continuous, dynamic transfer of nutrients in the soil-plant system, such as a farmer's field. It involves the exchange and movement of these elements and inorganic compounds that are essential to life between living and non-living components of the biosphere.
Nutrient pumping	Biological nutrient pumping refers to the tree-mediated transfer of nutrients from lower soil depths to surface layers.
Nutrient recovery	The extent to which nutrients are taken up by the current (and subsequent) season's crop.
Overstory (or overstorey)	The highest layer of vegetation, often the tree canopy, which grows over lower shrub or plant layers.
Perennial plant	A plant that grows for more than one year, in contrast to an annual, which grows for only one year (or season) before dying.
Permaculture	The conscious design and maintenance of agriculturally productive

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	ecosystems that have the diversity and resilience of natural ecosystems.
pH, soil	The negative logarithm of the hydrogen ion activity (concentration) of a soil (see under Reaction, soil).
Phenotypic plasticity	The property of a given genotype to produce different physiological or morphological phenotypes in response to different environmental conditions. E.g., shade adaptability and niche-compatibility of the species and cultivars grown in agroforestry combinations.
Photoperiodism	The distinctive response of plants (often in respect to flowering or seed germination) to exposures of daylight (in some cases artificial light) periods of different lengths.
Photorespiration	The light-dependent uptake of O_2 and the associated release of CO_2. It is a process in plant metabolism where the Calvin cycle enzyme Rubisco oxygenates RuBP and uses up some of the energy produced by photosynthesis.
Photosynthesis	A process of conversion of solar energy into biologically useful chemical energy that can be stored and transported.
Phytochrome	Light-absorbing pigment in plant tissues that control morphogenesis.
Pine-and-pasture	Pineforests of North America with deliberate management of both pasture and trees; also called cattle-under-pine system.

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Planted fallows	Quick growing trees planted during the fallow phase to overcome the problems of the traditional system and increase crop production.	
Pollarding	Cutting back the crown of a tree to harvest wood and to produce regrowth beyond the reach of animals and/or to reduce shading.	
Productivity, soil	The capacity of a soil for producing a specified plant or sequence of plants under a specified system of management. Productivity emphasizes the capacity of soil to produce plant products and should be expressed in terms of yields.	
Protein bank	Cut-and-carry fodder production systems involving leguminous trees and shrubs, grown intensively for a steady supply of fodder.	
Pruning	Cutting back plant growth, including side branches or roots.	
Rainfall erosivity (R)	The rainfall factor (R) of the Universal Soil Loss Equation (USLE).	
Ravines	The ultimate stage of water erosion caused by intense erosion over prolonged periods.	
Reaction, soil	The degree of acidity or alkalinity of a soil usually expressed as a pH value.	
	Extremely acid	<4.5
	Very strongly acid	4.5–5.0
	Strongly acid	5.1–5.5

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	Medium acid	5.6–6.0
	Slightly acid	6.1–6.5
	Neutral	6.6–7.3
	Mildly alkaline	7.4–7.8
	Moderately alkaline	7.9–8.4
	Strongly alkaline	8.5–9.0
	Very strongly alkaline	>9.0
REDD+	A global mechanism to reduce emissions from deforestation and forest degradation in the developing counties, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks (https://www.forestcarbonpartnership.org/what-redd).	
Reduced or minimum tillage	Also called conservation tillage, is a soil conservation practice of minimum soil manipulation necessary for successful crop production.	
Reforestation	Natural or intentional restocking of existing forests and woodlands (forestation) that have been depleted, usually through deforestation.	
Regeneration	Regrowth.	
Regenerative agriculture	A wide range of farming and grazing practices aimed at restoration and sustainable management of soil health through sequestration of soil organic carbon.	

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Relative growth rate	The increase in dry weight in a time interval in relation to the initial weight.
Relative humidity	The ratio expressed as percent, between the quantity of water vapor present and the maximum possible at given temperature and barometric pressure.
Resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change to still retain essentially the same function, structure, identity, and feedbacks.
Resorption	Re-translocation of nutrients from senescing leaves to younger parts of the plant.
Rhizobia	Bacteria capable of living symbiotically with higher plants, usually in nodules on the roots of legumes, from which they receive their energy, and capable of converting atmospheric nitrogen to combined organic forms; hence, the term symbiotic nitrogen-fixing bacteria (derived from the generic name *Rhizobium*).
Rhizodeposition	All material lost from plant roots, including water-soluble exudates, secretions of insoluble materials, lysates, dead fine roots, and gases such as CO_2 and ethylene.
Rhizosphere	The soil space in the immediate vicinity of plant roots.

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Riparian forest buffer	Strips of perennial vegetation (tree/shrubs/grasses) planted between croplands/pastures and streams, lakes, wetlands, ponds, etc. to reduce the impact of upland sources of pollution.
Root length density	Length of roots per unit area of soil surface (cm root cm^{-2} of soil surface) or per unit volume (cm root cm^{-3} of soil volume).
Root plasticity	The ability of tree roots to respond to changes in the local (belowground) environment caused by factors such as nutrient availability and impervious soil layers.
Root sucker	A shoot arising from the root of a plant.
Rotation	In agriculture, changing the crops grown on a particular piece of land (or crops and fallow) from season to season. In forestry, the length of time between establishment and harvesting of a plantation or tree.
Runoff	The portion of the precipitation on an area that is discharged from the area through stream channels. That which is lost without entering the soil is called "surface runoff" or overland flow and that which enters the soil before reaching the stream is called "groundwater runoff" or "seepage flow" from groundwater. In soil science, "runoff" usually refers to the water lost by surface flow; in geology and hydraulics, "runoff" usually includes both surface and subsurface flow.
Safety net (biological)	Safety net implies that tree roots "intercept" nutrients that are leached from the surface layers and reduce the nutrient loss through leaching.
Saline soil	Contains soluble salts at levels sufficient to impair crop production, with an electrical conductivity of the saturation soil extract of more than 4 dS/m at 25 °C but have an exchangeable sodium adsorption ratio < 15 and the pH is usually below 8.5.
Salinization	Excessive build-up of salts in crop root-zones, often caused by poor irrigation management in arid and semiarid regions. Primary salinization occurs by natural causes in arid and semiarid climatic zones; secondary salinization refers to that caused because of direct human activities.
Satoyama	The socio-ecological production landscape of Japan: a sequence of intimately linked agricultural land use systems such as woodlands, farmlands, settlements, and reservoirs, bordered on the upper reaches by forests (man-made or natural) (Chapter 11).
Screen function of trees	The phenomenon of reduced intensity of solar radiation and wind speed under trees, which in turn,

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	reduces the potential evapotranspiration (PET). As a result, in the arid and semiarid regions, herbage yields under shade are usually much higher (up to twice or more) than that in the open, and the grass remains greener for 4 to 6 weeks more at the end of the rainy reason. Human beings and livestock seek shade during mid-day when outside temperatures soar to more than 40 °C.
Semiarid	Regions or climates where moisture is more plentiful than in arid regions but still definitely limits the growth of most crop plants. Natural vegetation in uncultivated areas is short grasses, shrubs, and small trees.
Sequential cropping	Growing two or more crops in sequence on the same field per year. The succeeding crop is planted after the preceding crop has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time in the same field.
Shaded-perennial crop systems	Agroforestry systems in which trees are the main "crops" and other species – that could be annuals or woody or non-woody perennials – are grown beneath or between the "main" tree crops such that the main tree crops either provide shade to or receive shade from the companion species in the system.

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Shelterbelt or windbreak	Barriers of trees and shrubs used to reduce wind speed on farms and reduce the impact of tidal waves.
Shifting cultivation or swidden farming	A type of farming system in which land under natural vegetation is cleared, cropped – usually with food crops – for a few years, and then left untended while the natural vegetation regenerates; a few years later, the farmer returns to the site, clears it, and resumes crop cultivation.
Short-day plant	One that flowers in response to short days (day light 8–12 hours).
Shrub	A woody plant that remains less than 10 meters tall and produces shoots or stems from its base (see bush).
Silvoarable systems	Widely spaced woody vegetation intercropped with annual or perennial crops; another term for temperate alley cropping.
Silvopastoral system	Agroforestry practice of integrating trees, forage, and livestock on the same land management unit (see Chapters 9 and 10).
Slope (soil, land)	The inclination or angle of the land surface, which can be measured as a percent, ratio or in degrees or grades.
Small farm (small holding)	A farm that is more of a home than a business enterprise, so that farm-management decisions are made based on household needs rather than business interests.
Social forestry	The management and protection of forests and afforestation on barren lands to help in environmental,

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	social, and rural development.
Soil carbon saturation	A limit to the soil organic carbon (SOC) accumulation beyond which there is little or no increase in steady-state SOC stock with increasing C input levels.
Soil conservation	A combination of methods that safeguard the soil against depletion or deterioration caused by nature and/or humans.
Soil degradation	The physical, chemical, and biological decline in soil quality.
Soil erodibility factor (K)	A measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff.
Soil erosion	Detachment, transportation, and deposition of soil particles; water erosion and aeolic erosion: soil erosion caused by water and wind respectively.
Soil health	The continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans.
Soil organic matter	The organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil organisms.
Soil salinity	Refers to the extent of soluble salts in the soil (see Saline soils)

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Soil structure	The arrangement of the solid parts of the soil (sand, silt, clay) and the pore space located between them.
Soil texture	The proportions of sand, silt, and clay particles in the soil.
Sole cropping	Growing one crop alone (as opposed to intercropping/mixed cropping).
Specialty crops	Fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture).
Species	A taxonomic category below genus. A very closely related group of individual organisms which forms the basic unit for naming and classification according to distinguishable genetic characteristics.
Species diversity	Indicates how many divergent organisms occur in a particular area.
Species richness	An assemblage of populations of organisms in a given area.
Staggered (planting, harvesting)	Referring to activities carried out at different times or locations, instead of synchronized to occur at the same time or place.
Stem flow	Precipitation that drains from outlying leaves and branches and is channeled to the bole (or stem) of trees.
Stolon	Naturally horizontal, aboveground stem.

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Stool (plant)	The stump of a tree that has been felled or headed.
Stover	The mature cured stalks of maize or sorghum from which the grain has been removed.
Stress	Any factor that disturbs the normal functioning of an organism.
Streuobst	Traditional animal grazing system under fruit-tree orchards in Europe.
Stroma	The fluid-filled internal space of chloroplasts which is the locus for dark reactions.
Stubble mulch farming	Leaving the stubbles or crop residues on the land, which provides a surface cover during a fallow period. It can prevent soil erosion from wind or water and conserve soil moisture.
Succulent	A plant in which the tissues have an unusually high vacuole to cytoplasm ratio, thus very large cells.
Suckers	A side shoot from the roots of a plant; a side growth arising from an axillary bud.
Sun-loving (shade-intolerant)	Trees that require full sunlight to thrive and cannot grow in the shade of larger trees.
Sustainability	A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs.

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Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
Sustainable intensification (SI)	Increasing the yield output per unit of land while improving both environmental and social (livelihood) conditions.
Sustainable use	The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.
Synchrony hypothesis	Managing the release of nutrients, primarily nitrogen, from decomposing organic inputs, especially aboveground litter, to synchronize with periods of maximum nutrient demand by crops, without the risk of nutrient losses.
Taungya	The practice consists of growing annual crops along with the forestry species during the early years of establishment of the forestry plantation and is known by different names (see Chapter 5)
Temperate	Areas with large temperature extremes during the year; they have cold winters and warm rainy seasons.

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Temperate agroforestry	Agroforestry practiced in the industrialized temperate regions of the world generally between latitudes 30° and 60°. Five prominent temperate agroforestry practices are usually recognized: (1) Alley Cropping, (2) Riparian and Upland Buffers, (3) Windbreaks, (4) Silvopasture, and (5) Forest Farming, besides the emerging one, viz., Urban Food Forests.
Tenure	The right to property, granted by custom and/or law, which may include land, trees and other plants, animals, and water.
Terra preta	The biochar-rich dark-earth that appears in patches in a small region of the highly weathered, infertile Oxisols in Central Amazonia, Brazil.
Thinning	Intermediate cuttings that are primarily aimed at controlling the growth of stands by adjusting stand density.
Tiller	An erect or semi-erect, secondary stem which arises from a basal axillary or adventitious bud; an above-ground branch on a grass plant.
Topography	The physical description of land; changes in elevation due to hills, valleys, and other features.

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Traditional ecological knowledge (TEK)	A cumulative body of knowledge, belief, and practices, handed down through generations through traditional songs, stories and beliefs. It is concerned with the relationship of living beings (including human) with their traditional groups and with their environment.
Transpiration	The loss of moisture from plants in the form of water vapor.
Tree-crop interaction	Effect of trees of the agroforestry system on the performance of the other components as well as the whole system.
Trees outside Forest (TOF)	All trees excluded from the definition of forest and other wooded lands. Trees outside the forest are located on "other lands", mostly on farmlands and built-up areas, both in rural and urban areas.
Trub	A collective name for tree and shrub species.
Urban (and Peri-Urban) Forestry	Tree planting activities in urban/peri-urban areas primarily for aesthetic, environmental, and recreational purposes.
Urban food forest (UFF)	Urban forestry initiatives designed with food production objectives. It is emerging as a form of temperate agroforestry in the USA.
Vegetative buffer strips (VBS)	Areas of permanent vegetation located within

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	and between agricultural fields and the water courses to which they drain.
Vesicular arbuscular mycorrhiza (VAM) or arbuscular mycorrhiza (AM fungi)	A common endomycorrhizal association produced by phycomycetous fungi of the genus *Endogone* and characterized by the development of two types of fungal structures: (a) within root cells small structures known as arbuscles and (b) between root cells storage organs known as vesicles. Host range includes many agricultural and tree crops.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse

	effects of climate change, including climate variability and extremes.
Water productivity or water use ratio	Total dry matter produced (kg) per unit volume (m^3) of water.
Wild biodiversity	The diversity of forest plants, animals, and microorganisms.
Woodfuel	A broad term including firewood, charcoal, chips, pellets, and sawdust.
Woody	Plants that have wood as a part; not herbaceous.
Zero-grazing	Livestock production systems in which the animals are fed in pens or other confined areas and are not permitted to graze.

Appendix

SI Units and Conversion Factors

1 SI Units

The International System of Units, popularly known as the SI, has been used around the world as the preferred system of units and the basic language for science, technology, industry and trade, ever since it was established in 1960 by a resolution at the 11th meeting of the Conférence Générale des Poids et Mesures, the CGPM (known in English as the General Conference on Weights and Measures). The CGPM is the supreme authority of the International Bureau of Weights and Measures (BIPM, *Bureau International des Poids et Mesures*), an intergovernmental organization set up in 1875 under the terms of the *Metre Convention* with its headquarters near Paris to ensure worldwide unification of measurements. The 26th meeting of the CGPM held in November 2018 adopted a set of comprehensive changes to the SI; it came into force on 20 May 2019, the World Metrology Day, when the Metre Convention was signed in 1875.

The principal source of information on the SI is a booklet in French followed by a text in English titled "The International System of Units (SI), *ninth edition*" published by the BIPM (2019). Newell and Tiesinga (2019) edited the United States version of the English text of the brochure and was published by the National Institute of Standards and Technology (NIST) as Special Publication (SP) 330.

1.1 The SI Base Units

The SI covers units for every type of measurement, but at the heart of the SI is a set of seven units known as the "base units", as listed in Table 1.

1.2 SI Derived Units

Derived units are the products of powers of the base units. It may be expressed in terms of base units by means of mathematical symbols of multiplication and division. Certain derived units have been given special names and symbols, and these special names and symbols may themselves be used in combination with the SI and other derived units to express the units of other quantities. Table 2 lists 22 SI units with special names. Together with the seven base units (Table 1), they form the core of the set of SI units. All other SI units are combinations of some of these 29 units.

The CGPM has adopted a series of prefixes for use in forming the decimal multiples and sub-multiples of the coherent SI units (see Section 1.3). When the numerical factor of the product of powers of the base units is one, the derived units are called *coherent derived units*. The SI prefixes are convenient for expressing the values of quantities that are much larger than or much smaller than the coherent unit. However, when prefixes are used with SI units, the resulting units are no longer coherent, because the prefix introduces a numerical factor other than one. Prefixes may be used with any of the 29 SI units with special names except for the base unit,

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0

Table 1 SI base units

Base quantity		Base unit	
Name	Typical symbol[1]	Name	Symbol[2]
time	t	second	s
length	$l, x, r,$ etc.	meter	m
mass	m	kilogram	kg
electric current	I, i	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

[1]The symbols for quantities are generally single letters of the Latin or Greek alphabets, printed in italic font, and are *recommendations*

[2]The symbols for units are printed in an upright (roman) font and are *mandatory*

Table 2 The 22 SI units with special names and symbols

Derived quantity	Special name of the unit	Unit expressed in terms of base units	Unit expressed in terms of other SI units
plane angle	radian	rad = m/m	
solid angle	steradian	$\mathrm{sr} = \mathrm{m}^2/\mathrm{m}^2$	
frequency	hertz	$\mathrm{Hz} = \mathrm{s}^{-1}$	
force	newton	$\mathrm{N} = \mathrm{kg\ m\ s}^{-2}$	
pressure, stress	pascal	$\mathrm{Pa} = \mathrm{kg\ m}^{-1}\ \mathrm{s}^{-2}$	
energy, work, amount of heat	joule	$\mathrm{J} = \mathrm{kg\ m}^2\ \mathrm{s}^{-2}$	N m
power, radiant flux	watt	$\mathrm{W} = \mathrm{kg\ m}^2\ \mathrm{s}^{-3}$	J/s
electric charge	coulomb	C = A s	
electric potential difference	volt	$\mathrm{V} = \mathrm{kg\ m}^2\ \mathrm{s}^{-3}\ \mathrm{A}^{-1}$	W/A
capacitance	farad	$\mathrm{F} = \mathrm{kg}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^4\ \mathrm{A}^2$	C/V
electric resistance	ohm	$\Omega = \mathrm{kg\ m}^2\ \mathrm{s}^{-3}\ \mathrm{A}^{-2}$	V/A
electric conductance	siemens	$\mathrm{S} = \mathrm{kg}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^3\ \mathrm{A}^2$	A/V
magnetic flux	weber	$\mathrm{Wb} = \mathrm{kg\ m}^2\ \mathrm{s}^{-2}\ \mathrm{A}^{-1}$	V s
magnetic flux density	tesla	$\mathrm{T} = \mathrm{kg\ s}^{-2}\ \mathrm{A}^{-1}$	$\mathrm{Wb/m}^2$
inductance	henry	$\mathrm{H} = \mathrm{kg\ m}^2\ \mathrm{s}^{-2}\ \mathrm{A}^{-2}$	Wb/A
Celsius temperature	degree Celsius	°C = K	
luminous flux	lumen	lm = cd sr	cd sr
illuminance	lux	$\mathrm{lx} = \mathrm{cd\ sr\ m}^{-2}$	$\mathrm{lm/m}^2$
activity referred to a radionuclide	becquerel	$\mathrm{Bq} = \mathrm{s}^{-1}$	
absorbed dose, kerma	gray	$\mathrm{Gy} = \mathrm{m}^2\ \mathrm{s}^{-2}$	J/kg
dose equivalent	sievert	$\mathrm{Sv} = \mathrm{m}^2\ \mathrm{s}^{-2}$	J/kg
catalytic activity	katal	$\mathrm{kat} = \mathrm{mol\ s}^{-1}$	

kilogram. The seven base units and 22 units with special names and symbols are used in combination to express the units of other derived quantities. Table 3 lists some examples of derived quantities and the corresponding coherent derived units expressed in terms of base units.

Table 4 lists examples of coherent derived units whose names and symbols also include derived units. The complete set of SI units includes both the coherent set and the multiples and submultiples formed by using the SI prefixes.

1.3 SI Prefixes

SI prefixes are used to form decimal multiples and submultiples of SI units. They should be used to avoid very large or very small numeric values.

Table 3 Examples of coherent derived units in the SI expressed in terms of base units

Derived quantity	The typical symbol of quantity	Derived unit expressed in terms of base units
area	A	m^2
volume	V	m^3
speed, velocity	v	$m\ s^{-1}$
acceleration	a	$m\ s^{-2}$
wavenumber	σ	m^{-1}
density, mass density	ρ	$kg\ m^{-3}$
surface density	ρ_A	$kg\ m^{-2}$
specific volume	v	$m^3\ kg^{-1}$
current density	j	$A\ m^{-2}$
magnetic field strength	H	$A\ m^{-1}$
amount of substance concentration	c	$mol\ m^{-3}$
mass concentration	ρ, γ	$kg\ m^{-3}$
luminance	L_v	$cd\ m^{-2}$

Table 4 Examples of SI coherent derived units whose names and symbols include SI coherent derived units with special names and symbols

Derived quantity	Name of coherent derived unit	Symbol	Derived unit expressed in terms of base units
dynamic viscosity	pascal second	Pa s	$kg\ m^{-1}\ s^{-1}$
moment of force	newton meter	N m	$kg\ m^2\ s^{-2}$
surface tension	newton per meter	$N\ m^{-1}$	$kg\ s^{-2}$
angular velocity, angular frequency	radian per second	$rad\ s^{-1}$	s^{-1}
angular acceleration	radian per second squared	$rad\ s^{-2}$	s^{-2}
heat flux density, irradiance	watt per square meter	$W\ m^{-2}$	$kg\ s^{-3}$
heat capacity, entropy	joule per kelvin	$J\ K^{-1}$	$kg\ m^2\ s^{-2}\ K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	$J\ K^{-1}\ kg^{-1}$	$m^2\ s^{-2}\ K^{-1}$
specific energy	joule per kilogram	$J\ kg^{-1}$	$m^2\ s^{-2}$
thermal conductivity	watt per meter kelvin	$W\ m^{-1}\ K^{-1}$	$kg\ m\ s^{-3}\ K^{-1}$
energy density	joule per cubic meter	$J\ m^{-3}$	$kg\ m^{-1}\ s^{-2}$
electric field strength	volt per meter	$V\ m^{-1}$	$kg\ m\ s^{-3}\ A^{-1}$
electric charge density	coulomb per cubic meter	$C\ m^{-3}$	$A\ s\ m^{-3}$
surface charge density	coulomb per square meter	$C\ m^{-2}$	$A\ s\ m^{-2}$
electric flux density, electric displacement	coulomb per square meter	$C\ m^{-2}$	$A\ s\ m^{-2}$
permittivity	farad per meter	$F\ m^{-1}$	$kg^{-1}\ m^{-3}\ s^4\ A^2$
permeability	henry per meter	$H\ m^{-1}$	$kg\ m\ s^{-2}\ A^{-2}$
molar energy	joule per mole	$J\ mol^{-1}$	$kg\ m^2\ s^{-2}\ mol^{-1}$
molar entropy, molar heat capacity	joule per mole kelvin	$J\ K^{-1}\ mol^{-1}$	$kg\ m^2\ s^{-2}\ mol^{-1}\ K^{-1}$
exposure (x- and γ-rays)	coulomb per kilogram	$C\ kg^{-1}$	$A\ s\ kg^{-1}$
absorbed dose rate	gray per second	$Gy\ s^{-1}$	$m^2\ s^{-3}$
radiant intensity	watt per steradian	$W\ sr^{-1}$	$kg\ m^2\ s^{-3}$
radiance	watt per square meter steradian	$W\ sr^{-1}\ m^{-2}$	$kg\ s^{-3}$
catalytic activity concentration	katal per cubic meter	$kat\ m^{-3}$	$mol\ s^{-1}\ m^{-3}$

The International Electrotechnical Commission (IEC) has introduced the var (symbol: var) as a special name for the unit of reactive power. In terms of SI coherent units, the var is identical to the volt ampere

The prefix attaches directly to the name of a unit, and a prefix symbol attaches directly to the symbol for a unit (Table 5).

1.4 Non-SI Units

There are certain units, which are accepted for use with the SI. It includes units, which are in continuous everyday use, in particular the traditional units of time and of angle, together with a few other units, which have assumed increasing technical importance. There are also units, which are currently accepted for use with the SI to satisfy the needs of commercial, legal, and specialist scientific interests or are important for the interpretation of older texts (Table 6).

1.5 SI Conventions

There now exists a general consensus on how unit symbols and names, including prefix symbols and names as well as quantity symbols should be written and used, and how the values of quantities should be expressed. The most important of which are presented below, supports the readability and unambiguity of numerical results expressed in SI units.

1.5.1 Unit Symbols

- Unit symbols are printed in upright (roman) type regardless of the type used in the surrounding text.
- All unit names are written in small letters (newton or kilogram), except Celsius.
- An exception is that either capital L or lower-case l is allowed for the liter, in order to avoid possible confusion between the numeral 1 (one) and the lower-case letter l (el).
- A multiple or sub-multiple prefix, if used, is part of the unit and precedes the unit symbol without a separator. A prefix is never used in isolation and compound prefixes are never used.
- Unit symbols are mathematical entities and not abbreviations. Therefore, they are not followed by a period except at the end of a sentence, and one must neither use the plural nor mix unit symbols and unit names within one expression.
- In forming products and quotients of unit symbols the normal rules of algebraic multiplication or division apply. Multiplication must be indicated by a space or a half-high

Table 5 SI prefixes

Multiplying Factor	SI Prefix	Scientific Notation
1 000 000 000 000 000 000 000 000	yotta (Y)	10^{24}
1 000 000 000 000 000 000 000	zetta (Z)	10^{21}
1 000 000 000 000 000 000	exa (E)	10^{18}
1 000 000 000 000 000	peta (P)	10^{15}
1 000 000 000 000	tera (T)	10^{12}
1 000 000 000	giga (G)	10^{9}
1 000 000	mega (M)	10^{6}
1 000	kilo (k)	10^{3}
100	hecto (h)	10^{2}
10	deca (da)	10^{1}
1		10^{0}
0.1	deci (d)	10^{-1}
0.01	centi (c)	10^{-2}
0.001	milli (m)	10^{-3}
0.000 001	micro (μ)	10^{-6}
0.000 000 001	nano (n)	10^{-9}
0.000 000 000 001	pico (p)	10^{-12}
0.000 000 000 000 001	femto (f)	10^{-15}
0.000 000 000 000 000 001	atto (a)	10^{-18}
0.000 000 000 000 000 000 001	zepto (z)	10^{-21}
0.000 000 000 000 000 000 000 001	yocto (y)	10^{-24}

Table 6 Non-SI units accepted for use with the International System

Quantity	Name of unit	Symbol of unit	Value in SI Units
time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86 400 s
length	astronomical unit *(a)*	Au	1 au = 149 597 870 700 m
plane and phase angle	degree	°	1 = (π/180) rad
	minute	'	1' = (1/60)° = (π/10 800) rad
	second *(b)*	"	1" = (1/60)' = (π/648 000) rad
area	hectare *(c)*	ha	1 ha = 1 hm^2 = 10^4 m^2
volume	liter *(d)*	l, L	1 l = 1 L = 1 dm^3 = 10^3 cm^3 = 10^{-3} m^3
mass	tonne *(e)*	t	1 t = 10^3 kg
	dalton(f)	Da	1 Da = 1.660 539 066 60(50) × 10^{-27} kg
energy	electronvolt*(g)*	eV	1 eV = 1.602 176 634 × 10^{-19} J
logarithmic ratio quantities	neper *(h)*	Np	1 Np = 1
	bel *(h)*	B	1 B = (1/2) ln 10 (Np)
	decibel *(h)*	dB	

(*a*) As decided at the XXVIII General Assembly of the International Astronomical Union (Resolution B2, 2012)
(*b*) For some applications such as in astronomy, small angles are measured in arcseconds (i.e., seconds of plane angle), denoted as or ″, milliarcseconds, microarcseconds and picoarcseconds, denoted mas, μas and pas, respectively, where arcsecond is an alternative name for second of plane angle
(*c*) The unit hectare and its symbol ha, were adopted by the International Committee for Weights and Measures (CIPM) in 1879 (PV, 1879, 41). The hectare is used to express land area
(*d*) The liter and the symbol lower-case l were adopted by the CIPM in 1879 (PV, 1879, 41). The alternative symbol, capital L, was adopted by the 16th CGPM (1979, Resolution 6; CR, 101 and *Metrologia,* 1980, 16, 56–57) in order to avoid the risk of confusion between the letter l (el) and the numeral 1 (one)
(*e*) The tonne and its symbol t were adopted by the CIPM in 1879 (PV, 1879, 41). This unit is sometimes referred to as "metric ton" in some English-speaking countries
(*f*) The dalton (Da) and the unified atomic mass unit (u) are alternative names (and symbols) for the same unit, equal to 1/12 of the mass of a free carbon 12 atom, at rest and in its ground state. This value of the dalton is the value recommended in the CODATA 2018 adjustment
(*g*) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of one volt in vacuum. The electronvolt is often combined with the SI prefixes
(*h*) In using these units, it is important that the nature of the quantity be specified and that any reference value used be specified

(centered) dot (·), since otherwise some prefixes could be misinterpreted as a unit symbol.

- Division is indicated by a horizontal line, by a solidus (oblique stroke, /) or by negative exponents. When several unit symbols are combined, care should be taken to avoid ambiguities, for example by using brackets or negative exponents (Section 1.5.5).
- It is not permissible to use abbreviations for unit symbols or unit names, such as sec (for either s or second), sq. mm (for either mm^2 or square millimeter), cc (for either cm^3 or cubic centimeter), or mps (for either m/s or meter per second).
- Only units of the SI and those units recognized for use with the SI should be used to express the values of quantities.
- Unit symbols and unit names should not be mixed.
- A space is left between the numerical value and unit symbol (25 kg, but not 25-kg or 25kg). If the spelled-out name of a unit is used, the normal rules of English are applied.

1.5.2 Unit Names

- Unit names are normally printed in upright type and they are treated like ordinary nouns. In English, the names of units start with a lower-case letter (even when the symbol for the unit begins with a capital letter), except at the beginning of a sentence or in capitalized material such as a title. In keeping with this rule, the correct spelling of the name of the unit with the symbol °C is "degree Celsius" (the unit degree begins with a lower-case d and the modifier Celsius begins with an upper-case C because it is a proper name).

- When the name of a unit is combined with the name of a multiple or sub-multiple prefix, no space or hyphen is used between the prefix name and the unit name. The combination of prefix name and unit name is a single word.
- When the name of a derived unit is formed from the names of individual units by juxtaposition, either a space or a hyphen is used to separate the names of the individual units.

1.5.3 Formatting the Value of a Quantity

- The numerical value always precedes the unit and a space is always used to separate the unit from the number (Section 1.5.1). Thus, the value of the quantity is the product of the number and the unit. The space between the number and the unit is regarded as a multiplication sign (just as a space between units implies multiplication). The only exceptions to this rule are for the unit symbols for degree, minute and second for plane angle, °, ′ and ″, respectively, for which no space is left between the numerical value and the unit symbol

  E.g.,
  $m = 12.3$ g where m is used as a symbol for the quantity mass, but $\varphi = 30° \ 22' \ 8''$, where φ is used as a symbol for the quantity plane angle.

- This rule means that the symbol °C for the degree Celsius is preceded by a space when one expresses values of Celsius temperature t.

  E.g.,
  $t = 30.2$ °C
  but not $t = 30.2$°C
  nor $t = 30.2°$ C.

- Even when the value of a quantity is used as an adjective, a space is left between the numerical value and the unit symbol. Only when the name of the unit is spelled out would the ordinary rules of grammar apply, so that in English a hyphen would be used to separate the number from the unit

  E.g.,
  a 10 kΩ resistor, a 35-millimetre film.

- In any expression, only one unit is used. An exception to this rule is in expressing the values of time and of plane angles using non-SI units. However, for plane angles it is generally preferable to divide the degree decimally. It is therefore preferable to write 22.20° rather than 22° 12′, except in fields such as navigation, cartography, astronomy, and in the measurement of very small angles.

  E.g.,
  $l = 10.234$ m but not $l = 10$ m 23.4 cm.

1.5.4 Formatting Numbers, and the Decimal Marker

- The symbol used to separate the integral part of a number from its decimal part is called the decimal marker. The decimal marker shall be either the point on the line or the comma on the line. The decimal marker chosen should be that which is customary in the language and context concerned.
- If the number is between +1 and −1, then the decimal marker is always preceded by a zero.

  E.g.,
  −0.234, but not −.234.

- A space should be left between groups of three digits on either the right- or left-hand side of the decimal place (15 739.012 53). Neither dots nor commas are inserted in the spaces between groups of three.

  E.g.,
  43 279.168 29 but not 43,279.168,29.

- However, when there are only four digits before or after the decimal marker, it is customary not to use a space to isolate a single digit. The practice of grouping digits in this way is a matter of choice; it is not always followed in certain specialized applications such as engineering drawings, financial statements and scripts to be read by a computer.

  E.g.,
  either 3279.1683 or 3 279.168 3.

- For numbers in a table, the format used should not vary within one column.
- Mathematical operations should only be applied to unit symbols (kg/m^2) and not unit names (kilogram/cubic meter).
- Values of quantities should be expressed as 2.0 µs or 2.0×10^{-6} and not in terms such as parts per million.
- It should be clear to which unit symbol a numerical value belongs and which mathematical operation applies to the value of a quantity

E.g.,
35 cm × 48 cm, not 35 × 48 cm; or 100 g ± 2 g, not 100 ± 2 g.

- The value must apply to the whole symbol and not any particular unit within the symbol.

1.5.5 Multiplying or Dividing Quantity Symbols, the Values of Quantities, or Numbers

- When multiplying or dividing quantity symbols any of the following methods may be used:

ab, $a\ b$, $a{\cdot}b$, $a \times b$, a/b, $\frac{a}{b}$, $a\ b^{-1}$.

- When multiplying the value of quantities either a multiplication sign × or brackets should be used, not a half-high (centered) dot. When multiplying numbers, only the multiplication sign × should be used.
- When dividing the values of quantities using a solidus, brackets are used to avoid ambiguity. A solidus must not be used more than once in a given expression without brackets to remove ambiguities.

E.g.,
$F = ma$ for force equals mass times acceleration
(53 m/s) × 10.2 s or (53 m/s)(10.2 s)
25 × 60.5 but not 25 · 60.5
(20 m)/(5 s) = 4 m/s
(a/b)/c, not a/b/c.

1.5.6 Stating Quantity Values Being Pure Numbers

- Values of quantities with unit one, are expressed simply as numbers. The unit symbol 1 or unit name "one" are not explicitly shown. SI prefix symbols can neither be attached to the symbol 1 nor to the name "one", therefore powers of 10 are used to express particularly large or small values.

E.g.,
$n = 1.51$, but not $n = 1.51 \times 1$, where n is the quantity symbol for refractive index.

- Quantities that are ratios of quantities of the same kind (for example length ratios and amount fractions) have the option of being expressed with units (m/m, mol/mol) to aid the understanding of the quantity being expressed and also allow the use of SI prefixes, if this is desirable (µm/m, nmol/mol). Quantities relating to counting do not have this option, they are just numbers.
- The internationally recognized symbol % (percent) may be used with the SI. When it is used, a space separates the number and the symbol %. The symbol % should be used rather than the name "percent". In written text, however, the symbol % generally takes the meaning of "parts per hundred". Phrases such as "percentage by mass", "percentage by volume", or "percentage by amount of substance" shall not be used; the extra information on the quantity should instead be conveyed in the description and symbol for the quantity.
- The term "ppm", meaning 10^{-6} relative value, or 1 part in 10^6, or parts per million, is also used. This is analogous to the meaning of percent as parts per hundred. The terms "parts per billion" and "parts per trillion" and their respective abbreviations "ppb" and "ppt", are also used, but their meanings are language dependent. For this reason, the abbreviations ppb and ppt should be avoided. In English-speaking countries, a billion is now generally taken to be 10^9 and a trillion to be 10^{12}; however, a billion may still sometimes be interpreted as 10^{12} and a trillion as 10^{18}. The abbreviation ppt is also sometimes read as parts per thousand, adding further confusion.

2 Conversion Factors

2.1 Basic Conversion Factors

Quantity	SI Unit	Metric System (≈ SI)	English System
Length	1 m	100 cm = 10^{-3} km	39.37 inches = 3.281 feet
			1 inch = 2.54 cm
Area	1 m^2	10^4 cm^2 = 10^{-4} hectare	10.76 ft^2 = 1550 in^2
			1 ft^2 = 0.929 m^2
		1 hectare	2.47 acres
			1 acre = 0.4047 ha
Volume	1 m^3	10^6 cm^3 = 10^3 L	264.2 gallons (US)
		1 L	0.264 gal (US)
			0.212 gal (British)
			1 gal (US) = 3.786 L
			1 gal (British) = 4.55 L
			1 fluid ounce (US) = 29.6 mL
			1 ounce = 1/16 lb = 28.35 g
Mass	1 kg	1000 g	2.20462 pound (lb)
			1 lb = 0.454 kg
		t = 1 metric ton or tonne = 1000 kg	2204 lbs
			1 ton (US) = 2000 lb = 907.2 kg

2.2 Conversion Factors for SI and Non-SI Units (Source: ASA, CSSA, and SSSA, 2020)

To convert Column 1 into Column 2, multiply by	Column 1	Column 2	To convert Column 2 into Column 1 multiply by
	SI Unit	non-SI Unit	
	Length		
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, μm (10^{-6} m)	micron, μ	1.0
3.94×10^{-2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10^{-9} m)	Angström, Å	0.1
	Area		
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 $(10^3\ m)^2$	acre	4.05×10^{-3}
0.386	square kilometer, km^2 $(10^3\ m)^2$	square mile, mi^2	2.590
2.47×10^{-4}	square meter, m^2	acre	4.05×10^3
10.76	square meter, m^2	square foot, ft^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 $(10^{-3}\ m)^2$	square inch, in^2	645
	Volume		
9.73×10^{-3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83×10^{-2}
6.10×10^4	cubic meter, m^3	cubic inch, in^3	1.64×10^{-5}
2.84×10^{-2}	liter, L (10^{-3} m^3)	bushel, bu	35.24
1.057	liter, L (10^{-3} m^3)	quart (liquid), qt	0.946
3.53×10^{-2}	liter, L (10^{-3} m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10^{-3} m^3)	gallon (U.S.)	3.78
33.78	liter, L (10^{-3} m^3)	ounce (fluid), oz	2.96×10^{-2}
2.11	liter, L (10^{-3} m^3)	pint (fluid), pt	0.473
	Mass		
2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4

(continued)

To convert Column 1 into Column 2, multiply by	Column 1	Column 2	To convert Column 2 into Column 1 multiply by
	SI Unit	non-SI Unit	
2.205	kilogram, kg	pound, lb	0.454
10^{-2}	kilogram, kg	quintal (metric), q	10^{2}
1.10×10^{-3}	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (US), ton	0.907
1.102	tonne, t	ton (US), ton	0.907
	Yield and Rate		
0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, lb bu¯1	12.87
1.49×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon (US) per acre	9.35
893	tonnes per hectare, t ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447
	Specific Surface		
10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001
	Density		
1.00	megagram per cubic meter, Mg m^{-3}	gram per cubic centimeter, g cm^{-3}	1.00
	Pressure		
9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
2.09×10^{-2}	pascal, Pa	pound per square foot, lb ft^{-2}	47.9
1.45×10^{-4}	pascal, Pa	pound per square inch, lb in^{-2}	6.90×10^{3}
	Temperature		
1.00 (K –273)	Kelvin, K	Celsius, °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F – 32)
	Energy, Work, Quantity of Heat		
9.52×10^{-4}	joule, J	British thermal unit, Btu	1.05×10^{3}
0.239	joule, J	calorie, cal	4.19
10^{7}	joule, J	erg	10^{-7}
0.735	joule, J	foot-pound	1.36
2.387×10^{-5}	joule per square meter, J m^{-2}	calorie per square centimeter (langley)	4.19×10^{4}
10^{5}	newton, N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter, W m^{-2}	calorie per square centimeter minute (irradiance), cal cm^{-2} min^{-1}	698
	Transpiration and Photosynthesis		
3.60×10^{-2}	milligram per square meter second, mg m^{-2} s^{-1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56×10^{-3}	milligram (H_2O) per square second, mg m^{-2} s^{-1}	micromole (H_2O) per square centimeter second, μmol cm^{-2} s^{-1}	180
10^{-4}	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square centimeter second, mg cm^{-2} s^{-1}	10^{4}
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm^{-2} h^{-1}	2.78×10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75×10^{-2}
	Electrical Conductivity, Electricity, and Magnetism		
10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	0.1
10^{4}	tesla, T	gauss, G	10^{-4}
	Water Measurement		
9.73×10^{-3}	cubic meter, m^3	acre-inch, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, m^3 h^{-1}	cubic feet per second, ft^3 s^{-1}	101.9

(continued)

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1 multiply by
4.40	cubic meter per hour, $m^3\ h^{-1}$	U.S. gallons per minute, gal min^{-1}	0.227
8.11	hectare meter, ha m	acre-foot, acre-ft	0.123
97.28	hectare meter, ha m	acre-inch, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare centimeter, ha cm	acre-foot, acre-ft	12.33
	Concentrations		
1	centimole per kilogram, cmol kg^{-1}	milliequivalents per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1
	Radioactivity		
2.7×10^{-11}	becquerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	becquerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01
	Plant NutrientConversion		
	Elemental	Oxide	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602

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