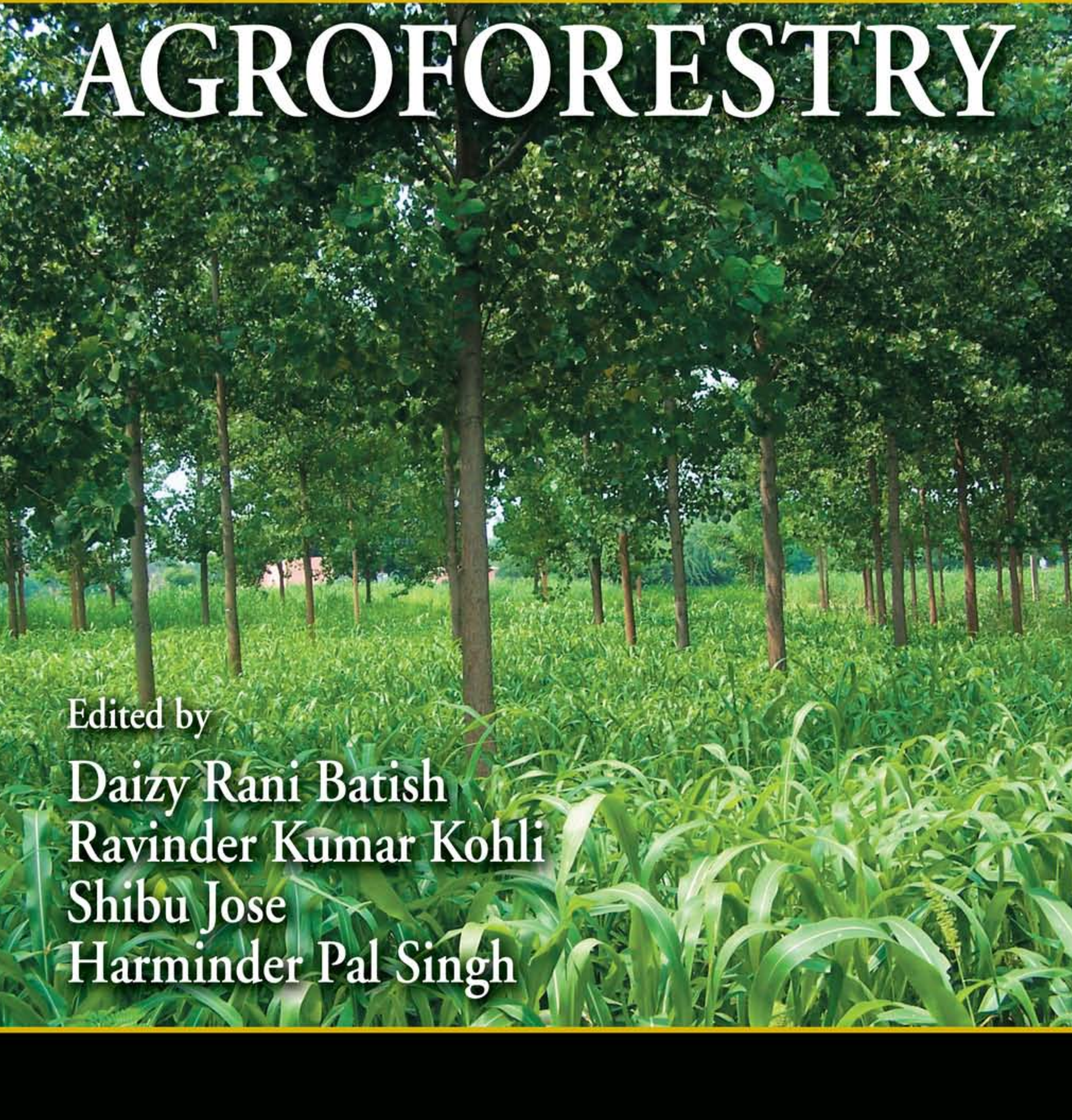
ECOLOGICAL BASIS OF AGROFORESTRY



Edited by

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Preface

The world at present is facing innumerable problems such as burgeoning population, ecosystem degradation, particularly in the tropics, declining agricultural productivity, and changing environment. In order to sustain in the future, it is essential to find solutions to these problems, particularly with regard to ensuring food security and coping with the changing environment. Existing approaches to enhance productivity and mitigate environmental degradation are inadequate. Proper land-use patterns, sustainable agroecosystems, and resource management are possible alternatives to these problems. Agroforestry—a traditional practice of combining trees with agricultural crops or pasture—can contribute substantially in this direction through its multiple benefits and ecosystem services. If properly designed, agroforestry may help in alleviating poverty, providing food security and livelihood, maintaining ecosystem health, managing pest and weeds, conserving biodiversity, and mitigating greenhouse effects by carbon sequestration. Conversely, a poorly designed agroforestry system may lead to problems such as loss of productivity due to resource competition and allelopathy or negative effects of shading, aggravated problems of pest and weed infestation, loss of diversity, and ecosystem degradation due to the introduction of invasive species.

For an agroforestry system to be profitable, better understanding of various ecological processes that govern these complex systems is required. This volume aims at providing knowledge as to how ecologically sustainable agroecosystems can meet the challenges of enhancing crop productivity, soil fertility, and environment sustainability. The topics of the 19 chapters were carefully selected to accomplish the above objectives. These are divided into four sections—Ecological Interactions: An Overview (seven chapters), Belowground Ecology (six chapters), Models in Agroforestry (two chapters), and Ecological Economics (four chapters).

Part I focuses on various tree–crop interactions in different ecoregions of the world. Various above- and belowground interactions, especially in alley-cropping systems in temperate zones, have been critically analyzed and will be of immense help to readers. Among various interactions that affect crop productivity, allelopathy—a chemical-mediated interplant interaction—has often been rejected because of lack of sufficient field demonstration. A chapter is devoted to this important aspect of chemical ecology, which also highlights how allelopathy and the chemicals involved therein can be put to some practical use. The proof of attempt has also been made to include other important issues such as tri-trophic interactions and ecologically based pest management in agroforestry and how crop production can be enhanced. Part II is devoted to root-mediated belowground interactions in agroforestry systems and their role in enhancing crop productivity, soil fertility, and sustainability. An exhaustive study on litter dynamics in plantation and agroforestry systems and various factors affecting nutrient release may be beneficial to readers. Part III provides insight into the role of ecological modeling of complex agroforestry systems such as shelterbelts and how they help in choosing suitable computer-based designs to gain profitability. Part IV deals with various socioeconomic aspects of agroforestry and technological tools that benefit society in different eco-regions of the world. It also intends to supply in-depth knowledge on various farming systems and technologies that help enhance the socioeconomic status of farmers and provide environmental benefits to land users.

In sum, efforts have been made to integrate the relevant information on various ecological processes in the agroforestry system into a single comprehensive volume that will be useful to university teachers, students, researchers, agroforestry specialists, landscapists, agriculture and forestry extension workers, scientists, and farmers.

We offer our sincere thanks to all the authors and reviewers for their commendable contributions and cooperation.

Daizy Rani Batish
Ravinder Kumar Kohli
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Part I

Ecological Interactions: An Overview

1 Ecological Interactions in Agroforestry: An Overview

Ravinder Kumar Kohli, Harminder Pal Singh, Daizy Rani Batish, and Shibu Jose

CONTENTS

1.1 INTRODUCTION

Agroforestry is one of the sustainable approaches to land-use management where both agriculture and forestry combine into an integrated production system to get maximum benefits (Kidd and Pimentel, 1992; Nair, 1998). As per ICRAF (International Centre for Research in Agroforestry, now World Agroforestry Centre), "agroforestry is a deliberate integration of woody components with agricultural and pastoral operations on the same piece of land either in a spatial or temporal sequence in such a way that both ecological and economic interactions occur between them." Incorporation of the trees under agroforestry systems (AFS) to harvest potential benefits of trees offers a good option under Low Input Sustainable Agriculture (LISA). In fact, it is an age-old practice revived in the recent past with a renewed scientific interest to maintain the sustainability of agroecosystems (Noble and Dirzo, 1997). The revival of agroforestry became inevitable to meet growing demands of increasing population, to compensate forests in the wake of fast increasing rate of deforestation and soil degradation, both in the tropics and temperate regions of the world, and to conserve biodiversity. Agroforestry provides one of the best alternatives for planting trees outside forests. In other words, it is a collective name for sustainable land-use system to get social, economical, and environmental benefits (Sanchez, 1995). It leads to a more diversified and sustainable system than other croplands without trees. Griffith (2000) considers agroforestry as an ecologically sustainable land-use option alternative to the prevalent subsistence farming patterns for conservation and development, particularly in the tropics. Though practiced in the majority of ecoregions, agroforestry is more common in the tropics. According to a report of the World Bank, around 1.2 billion rural people currently practice agroforestry the world over (World Bank, 2004). There are more than 2000 tree species used in agroforestry (Rao et al., 2000). AFS have been classified based on structural, functional, physiognomy, floristics, socioeconomic, and ecological aspects (Nair, 1993; Ffolliott, 2003). However, classification based on structural components is very common.

Nair (1998) pointed that the concept of agroforestry, which popularized during the 1990s, has passed through stages of hypothesis making and experimentation and now focuses on science and technology to get a better and wider applicability. Sanchez (1995) opined that the science of agroforestry centers around four factors—competition, complexity, sustainability, and profitability and there should be a balance among all these factors to get fruitful results. In fact, agroforestry is substantially assisting in meeting the United Nations Millennium Development Goals (MDG) such as eradication of poverty and hunger, better health, nutrition and education to people, gender equality, and environmental sustainability, particularly in developing countries (Garrity, 2004, 2006). In other words, agroforestry is an integrated science that helps in bridging the gap between the need for conservation and meeting people's demand at the same time.

However, there are several limitations linked with agroforestry. These include competition of trees with crops for resources, allelopathic effects of trees on crops, rapid growth of some tree species within agricultural fields occupying the space of crops, entry of invasive species in the agricultural land, and trees serving as habitat for harmful pests and diseases. To gain maximum benefits from AFS, it is essential to minimize the negative concerns linked to it. In fact, the ecological sustainability and success of any AFS depend on the interplay and complementarity between positive and negative interactions. It can yield positive results only if positive interactions outweigh the negative interactions.

1.2 ECOLOGICAL INTERACTIONS UNDER AFS

An ecological interaction refers to the major impact of one species on the other or on the same type of species. In general, there are three types of interactions: neutral, positive, and negative. Among these, neutral interactions are very rare and happen only when the niches are wide apart. Specifically, the interactions in AFS can be complementary (positive), supplementary (neutral), or competitive (negative) (van Noordwijk and Hairiah, 2000). Further, these can be belowground or aboveground. In agroforestry, particularly simultaneous systems, trees (being perennial, large-sized, and dominant) have a major and continuous influence on the crops and determine the extent of interactions (Ong, 1995). Further, due to well-developed root systems and better adaptability toward environmental stresses, trees are able to modify AFS for their own benefit. Additionally, trees generally have their roots well below the crop zone, use water from the lower soil layers, and thus do not affect crop. Rather, tree roots act as safety nets and capture the nutrients that are lost because of leachation (van Noordwijk and Hairiah, 2000). Swift et al. (2006) pointed that incorporation of trees within any land-use system results in a large number of secondary interactions. AFS are much more complex than the sole cropping system because of the nature and arrangement of the components and their unequal size. Initially, the research on tree–crop interactions in AFS received little attention of scientists and researchers; however, it has recently gained the momentum world over (Rao et al., 1998). Various positive and negative interactions of trees with crops, particularly under simultaneous agroforestry system (SAFS), are given in Table 1.1. Competition and allelopathy, in addition to the shading, harboring of the enemies of the crops, and invasive potential of some of the introduced tree species, are the predominant negative interactions. On the other hand, positive interactions include improvement of soil fertility through addition of tree litter, natural weed and pest management through allelochemicals of trees or through chemical signaling,

TABLE 1.1
Various Types of Positive and Negative Impacts of Trees on Crops under AFS

Positive Effects	Negative Effects
Soil fertility enrichment	Shading
Improvement of microclimate	Resource competition
Maintenance of water quality	Allelopathy (chemical interference)
Weed and pest management	Invasive behavior of some of the introduced species
Biodiversity conservation	Harboring of harmful pathogens and pests
Enhancing food security	
Alleviating poverty	
Carbon sequestration and greenhouse gas mitigation	
Habitat for wildlife	
Phytoremediation	

modification of microclimate, environmental mitigation and phytoremediation, habitat for wildlife, and conservation of soil, moisture, and biodiversity through the protective roles of trees. The direction and magnitude of these interactions, however, may depend on patterns of resource sharing and the time at which these patterns are determined (Rao et al., 1998).

1.2.1 Positive Effects (Complementarity)

1.2.1.1 Improvement of Soil Fertility and Microclimate

Land degradation and declining soil fertility pose a major threat to agricultural productivity. Use of synthetic fertilizers to replenish soil nutrients fails to provide adequate solution. Incorporation of trees in the croplands can help in maintaining the nutrient pool and enhance soil fertility both under sequential and simultaneous agroforestry (Young, 1997; Rao et al., 1998; Giller, 2001; Thevathasan and Gordon, 2004; Jama et al., 2006b). Tejwani (1994) reported that AFS are an excellent strategy for reclamation of salt-affected soils. Tree litter and prunings improve soil fertility not only through the release of nutrients in the soil by mineralization but by also adding soil organic matter. However, it depends on the quality and quantity of tree litter or prunings, soil type, and climatic conditions of the area. Hulugalle and Ndi (1994) demonstrated that hedgerows of Senna (*Senna spectabilis* [DC] Irwin & Barneby) and Flemingia (*Flemingia congesta* [Willd.] Merrill) significantly improved soil properties in a newly cleared Ultisol (Typic Kandiudult) in southern Cameroon. A significant increase was observed in exchangeable Ca, CEC, and water infiltration in the alleys of both the species. Chander et al. (1998) demonstrated that adoption of *Dalbergia sissoo* Roxb. ex DC., a N-fixing tree, under agroforestry significantly increased nutrient pool, organic biomass, and activities of enzymes—hydrogenases and alkaline phosphatases—in the soil. Further, agroforestry trees also help in improving soil physical and biological properties (Rao et al., 1998). Thevathasan and Gordon (2004) reported that tree intercropping under temperate AFS significantly enhanced the diversity of birds, insects, and earthworms; increased soil organic carbon content and N cycling; and improved soil health. In general, the mechanisms by which trees improve soil physicochemical and biological properties are as follows:

1. Release of nutrients from tree litter and prunings
2. Nitrogen input through biological nitrogen fixation (through N-fixing trees)
3. Phosphorus input through mycorrhizal associations

4. Reduced soil erosion and nutrient leaching
5. Nutrient capture from the subsoil through deep-rooted trees
6. Redistribution of nutrients through lateral roots of some trees

Another positive interaction between trees and crops is the improvement of microclimate through modification of temperature to reduce heat stress and evapotranspiration, improvement of crop–water efficiency and energy balance (Brenner, 1996; Jose et al., 2004).

1.2.1.2 Maintaining Water Quality

Agroforestry can also help in improving water quality by reducing levels of pollution and soil erosion and thus landscape amelioration (Nair and Graetz, 2004; Schultz et al., 2004). For example, riparian buffer zones, if well designed and properly located, can be very helpful in this direction (Dosskey, 2002). These buffers help in reducing the transport of polluted runoffs to the rivers and streams. Agroforestry also improves water-use efficiency and increases environmental sustainability. In addition, trees increase the water-holding capacity of the soil, reduce soil evaporation, increase water infiltration into the soil (Nair, 1993), and efficiently capture rainwater compared with traditional agricultural practices (Lott et al., 2002). Of late, it has been proposed that trees can efficiently increase water productivity, particularly under semiarid regions (Ong and Swallow, 2003; Ong et al., 2007).

1.2.1.3 Weed and Pest Management

In tropical and temperate agroecosystems, weeds and pests interact and interfere with crop plants and cause enormous harm to crop productivity. Their management is a big challenge and the indiscriminate use of synthetic herbicides and pesticides for controlling them has led to a number of problems like toxicological effects on the nontarget species, environmental degradation, and loss of sustainability of croplands. Presence of trees in agricultural lands may reduce weed populations because of the shading effect of trees, availability of less space for their growth, shifts in species composition, and altered environmental conditions (Liebman and Staver, 2001; Sileshi et al., 2006). Jama et al. (1991) demonstrated that alley cropping with *Leucaena leucocephala* (Lam.) de Wit reduced weed density by 90% and increased maize yield by 24%–76%. Incorporation of trees into the cropping system, particularly in the east and west Africa, holds a good potential for the control of parasitic weeds. For example, Gworgwor (2007) observed that *Faidherbia albida* (Del.) A. Chev. trees can fully eliminate *Striga hermonthica* (Del.) Benth. from pearl millet fields.

AFS create a landscape that is important for biological pest control (Pandey, 2007). However, there are conflicting reports regarding the potential beneficial effects of trees in agroforestry for disease and pest management. Studies have indicated that due to modification of microclimate, water regime, moisture, air humidity, and surface temperature, the number of insects, pests, and pathogens increases, particularly near the tree line (Schroth et al., 2000). In contrast, other studies have indicated that trees, particularly as windbreak or hedgerow or shelterbelt, act as barrier to airborne pests and pathogens, repel them, and thus have a protective action (Rao et al., 2000; Sileshi et al., this volume, Chapter 5). In addition, trees may provide more habitats for enemies of insect pests and thus more options for pest management (Middleton, 2001).

Further, allelopathic effects of tree mulch, prunings, and residues can also be useful in weed suppression (Singh et al., 2003). Allelochemicals from trees can be used for sustainably managing the weeds on the pattern of herbicides and pesticides. For example, ailanthone from tree of heaven (*Ailanthus altissima* [Mill.] Swingle), volatile monoterpenes as well as crude oil from *Eucalyptus* species, mimosine from *L. leucocephala*, and caffeine from *Coffea arabica* L. (Rizvi et al., 1999; Singh et al., 2003). Even plant–plant signals through allelochemicals within the soil can be exploited for weed management in a practical way rather than studying their direct physiological effects on the other plants (Birkett et al., 2001). For this, desirable allelopathic trees could be intercropped with crops to achieve weed management through rhizospheric allelochemicals-based signals.

1.2.1.4 Conserving Biodiversity

Biodiversity loss, particularly due to deforestation, is one of the major causes of worry to scientists. Agroforestry helps in reducing biodiversity loss by providing a protective tree cover along agricultural fields. The presence of trees further enhances diversity by providing shelter and habitat to a diversity of other flora and fauna. It also helps in conserving genetic diversity of ethnocultivars or landraces and trees that are in danger of loss and require priority conservation (Noble and Dirzo, 1997; Pandey, 2007). Further, it also helps in conserving traditional knowledge about the conservation of wild varieties of trees and other plants. Studies have shown higher biodiversity levels and species richness in AFS than in sole cropping systems (Estrada et al., 1993; Perfecto et al., 1996; Thevathasan and Gordon, 2004). Agroforestry helps in biodiversity conservation through (1) provision of secondary habitats for species, (2) reduction in the rate of conversion of natural habitats, and (3) creation of a benign and permeable matrix between habitat remnants (Schroth et al., 2004; McNeely and Schroth, 2006). AFS enhance diversity both at the site level as well as at the landscape level. At a given site, AFS have more diversity both at above- and belowground levels than the sole cropping system (Vandermeer, 2002; Ruark et al., 2003). AFS also provide refuge to species in the event of some catastrophic fire (Griffith, 2000). Gillison et al. (2004) reported that complex AFS and shade-grown coffee had higher biodiversity levels than simple sun-grown coffee; however, it was lesser than in the primary forests.

Although AFS have less species diversity than the tropical forest, they have a variety of species diversity compared with traditional agricultural systems. Their rich diversity makes them ecologically resilient and thus gives them the ability to provide more and better ecological functions (Olson et al., 2000; Vandermeer, 2002). Altieri (1995) opined that since AFS are more diverse and have low-input strategies, these have greater biological interactions and thus are richer in biodiversity. Increased biodiversity further enhances chances of bioprospecting, that is, searching for new chemicals and plant-based products for the welfare of humanity. Guo (2000) viewed AFS as an excellent land-use practice for biodiversity conservation and sustainable development in the tropics. AFS also helps in reducing the dependence of local peasants or farmers on the natural resources of the protected areas—national parks and sanctuaries (Murniati et al., 2001).

1.2.1.5 Enhancing Food Security and Alleviating Poverty

Trees are the sources of a number of valuable and marketable products. Agroforestry helps in providing an opportunity to marginal and low-income farmers to improve their livelihood by marketing these products as household food, medicine, small timber, domestic wood supply, fiber, or fuel. It thus provides both food and economic security to farmers, particularly in the tropics (Garrity, 2004). Recently, agroforestry has been suggested to play a central role in improving food security, alleviating poverty, and natural resource management, particularly in east and central African regions (Ashley et al., 2006; Jama et al., 2006a; Leakey et al., 2006). Agroforestry adoption has also been viewed as a viable option to provide support in the form of value-added products (i.e., food, medicine, timber), livelihood, and income to HIV- or AIDS-affected communities, particularly in very poor regions of the world like sub-Saharan Africa (Garrity, 2004, 2006; Leakey et al., 2006). Leakey et al. (2006) advocated agroforestry as a new approach for sustainable rural development. However, much needs to be done in this direction to include underutilized and medicinal tree species, which can offer good economic returns to the farmers in addition to providing other benefits of AFS.

1.2.1.6 Carbon Sequestration and Greenhouse Gas Mitigation

World over, scientists are facing the challenging problem of loss of carbon (C) stocks in the terrestrial ecosystems and increase in the levels of green house gases in the atmosphere. AFS have a great scope in sequestering aboveground and belowground (soil) C and help in mitigating the greenhouse effect by reducing C emissions (Dixon et al., 1994; Wang and Feng, 1995; Batjes and Sombroek, 1997; Pandey, 2002; Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Lal, 2005). Trees can store C both *ex situ* (products) as well as *in situ* (biomass and soil) and are considered as effective C sinks (Montagnini and Nair, 2004). Though the exact potential of agroforestry trees for this purpose is largely unknown, yet some preliminary reports are available. AFS, particularly in the tropics, can even ease the environmental degradation caused by deforestation and reduce the pressure on natural forests (Dixon, 1995). He estimated that AFS on 1 ha of land could compensate the loss caused by 5–20 ha of deforestation. Recently, agroforestry practices in humid tropics have been reported to reduce soil emission of N_2O and CO_2 and increase the CH_4 sink strength when compared to agricultural systems (Mutuo et al., 2005). However, extensive research is required to quantify exactly this underexploited C sequestration potential of AFS, in general, and under specific management patterns.

Similar to the impact on global C balance, AFS can also ameliorate the greenhouse gas, particularly nitrous oxide (N_2O), emission. Liang and Thevathasan (2003) demonstrated that intercropping of *Populus* into AFS reduced N_2O emissions by 0.69 kg hm^{-2} a^{-1}. Thevathasan and Gordon (2004) reported that trees intercropped in AFS reduce the N_2O emissions due to reduced fertilizer use and efficient N cycling. However, the mitigation of greenhouse gas emission under AFS varies greatly with the tree species used and depends on the C:N ratio, polyphenol content, and protein-binding capacity (Millar and Baggs, 2004).

1.2.1.7 Phytoremediation and Environmental Clean-Up

Garrett and Buck (1997) suggested that AFS including trees as intercrops, riparian plantations, shelterbelts, and windbreaks have a good potential for cleaning up the contaminated soils. Schultz et al. (1995) reported that multispecies riparian buffer strips are very effective in stopping sediments and flow of runoff nutrients, pesticides, and fertilizers. In this direction, short-rotation woody trees like *Populus*, *Salix*, *Eucalyptus*, *Pinus*, and *Acacia* spp. incorporated under AFS hold a great potential for remediation of soil contaminated with heavy metals, pesticides, herbicides, and organic compounds (Rockwood et al., 2004).

1.2.2 Negative Effects

A number of negative interactions such as shade, competition, allelopathy, harboring of harmful pests, and threat from invasive potential of trees prevail under AFS (Table 1.1).

1.2.2.1 Shading Effect

Although the reports available in the literature concerning the effects of shade or competition for light vary greatly, shading by agroforestry trees generally has negative effects on crop productivity. However, it depends on soil type, climate, crop or tree species, and the management practices (Ong and Huxley, 1996; Huxley, 1999). On the other hand, shading may have either no (Gillespie et al., 2000) or even positive effect on associated crops under a given set of environmental conditions. For example, shading by trees increased forage yield (Lin et al., 1999), reduced pest density in intercrops (Stamps and Linit, 1998), and decreased weed density and increased maize yield (Jama et al., 1991). However, it depends on the soil fertility status, especially the N content.

The physiological mechanism by which shading affects crop productivity could be the interception of photosynthetically active radiations (PAR) and thus the quantity and quality of light reaching crops (Chirko et al., 1996), and differences in carbon fixation pathways, that is, C_3 or C_4

plants (Jose et al., 2004). Pillar et al. (2002) demonstrated the shading effect of *Eucalyptus* spp. on grass communities and indicated that differences occurred in cover abundance of C_3 and C_4 species. Increased shading by tree canopy reduced the cover abundance of C_4 species and increased the number of C_3 species (Pillar et al., 2002).

1.2.2.2 Resource Competition

Competition for essential growth substances including water and nutrients is one of the most severe negative effects that trees can have on crops (Nair, 1993). If improperly selected and managed, trees in AFS strongly compete with crops for light, resources, shade, and water and thus can have a devastating effect on crop yields (García-Barrios, 2003). However, it largely depends on the climate, soil type, management practices, tree–crop combination, and fertility patterns. Its intensity and type varies with the geographical region, that is, tropical or temperate area, or arid, semiarid, or wet type (Nair, 1993; Huxley, 1999). For example, in a humid region where there is enough moisture, competition normally exists for light or nutrients, whereas in a semiarid or arid zone, the trees and crops compete for moisture and nutrients, though there is adequate light (Nair, 1993; Huxley, 1999). The choice of tree component is very important since studies have shown that fast-growing tree species are not good for hedgerow species (Broadhead et al., 2003; De Costa and Surenthran, 2005). However, trees in agroforestry, particularly in dry and semiarid regions, can be managed to optimize their water use and productivity by root and shoot pruning to decrease underground competition, avoiding fast growing evergreen species like *Eucalyptus*, and opting for deciduous tree species that use little water during dry seasons (Ong et al., 2007). Further, selection of tree species should be done keeping in mind the phenology so that there is no extra burden on the water regime, particularly during the dry seasons. For example, trees like *F. albida* should be avoided in dry areas as they produce leaves and branches during dry season and demand more water (Ong et al., 2007). The severity of the competition further depends on the architecture of the tree and crop root systems. A complementarity between tree and crop roots is essential to minimize resource competition and maximize resource use (Huxley, 1999). Cannell et al. (1996) opined that tree incorporation in crops is beneficial only if the trees can capture resources not used by crops. A number of earlier studies have reported that removal of root competition significantly increases yield (Corlett et al., 1992; De Costa and Surenthran, 2005). Management of competition between tree and crops is very important, especially under SAFS; and if properly managed, it can lead to a successful system.

1.2.2.3 Allelopathy

Allelopathy is another negative interaction between trees and crops that operates under SAFS. It mediates through the release of chemicals by one plant into the surrounding environment and retards or suppresses the growth of other plants. Allelopathy causes crop losses under conditions of unsuitable tree–crop combination, for example, eucalypts (*Eucalyptus* sp.), poplar (*Populus deltoides* Bartr. ex Marsh), and black walnut (*Juglans nigra* L.) planted under SAFS. Allelochemicals—the chemicals responsible for allelopathic effects—may be present in any part of the tree (Rice, 1984). However, their effects under field conditions are a function of their bioactive concentrations in the soil, and depend upon prevailing environmental conditions (Rice, 1984). Studies on allelopathy are available from both under temperate as well as tropical AFS (Rao et al., 1998; Rizvi et al., 1999; Jose et al., 2004).

Allelopathic implications of trees in AFS have been discussed in detail in Chapter 3 of this book.

1.2.2.4 Exotic Invasive Species

One of the major problems linked with agroforestry trees is that some of them, particularly exotics, have a tendency to become weedy and invade other ecosystems. Such trees when incorporated in AFS can negate the perceived economic returns (Richardson et al., 2004). Further, they escape into the nearby ecosystems, outcompete the native vegetation, and threaten native plant communities. It has been estimated that of the 2000 trees frequently used under agroforestry programs, at least 135 acquired weedy character under some situations, whereas 25 were frequently weedy, which included *L. leucocephala* and *Prosopis* sp. (Richardson, 1998). Recently, in a review of invasive trees by CAB International, 194 species used in agroforestry have been classified as invasive. Prominent agroforestry tree species such as *Pinus*, *Eucalyptus*, *Acacia, Sesbania, Crotalaria,* and *Senna* also possess weedy character outside their natural range (Richardson et al., 2004). A number of *Pinus* species are serious invaders and colonizers in the southern hemisphere. Several species of *Acacia* introduced from Australia for agroforestry purposes have become invasive (Richardson et al., 2004). The reasons for their acquiring weedy habits include fast growth rate, remarkable adaptability in the alien environment, rapid ability to colonize, high reproductive rate, and ability to outcompete or suppress other plants. *L. leucocephala*—one of the most important agroforestry tree species—is also a serious invader and a noxious weed in 20 countries (Hughes, 2006). It is a prolific seed producer and forms its own monospecific thickets that are difficult to eradicate. It has also been included in the list of 100 worst invaders of the world (Hughes, 2006). Thus, there is an urgent need to predict and assess the risks of agroforestry tree species becoming weedy before their introduction and widespread promotion into new environment; however, it is very challenging.

1.3 CONCLUSIONS AND WAY FORWARD

From the above discussion, it is pertinent that agroforestry has a great scope and potential in terms of social, economic, and environmental services. Bene et al. (1977) rightly pointed out that agroforestry has a great potential to improve the life of people within a reasonably short time, particularly in the developing countries. McNeely (2004) advocated AFS as a unique ecological system that favours both crop productivity and biodiversity conservation, and thus is a best example of ecoagriculture. Garrity (2006) viewed agroforestry as a science and practice in achieving the United Nations MDG eradicating hunger and poverty, thus improving the livelihood of farmers and advancing health and nutrition. However, it depends on the complementarity between negative and positive interactions (effects) of AFS and minimization of negative concerns. However, the problem is where and how to integrate these strategies to achieve a balance between potential conservation benefits, on the one hand, and the sustainable rural development, on the other (van Noordwijk et al., 1997). In other words, there is a need to develop agroforestry as an ecologically sustainable land-use system that involves interplay between various positive and negative interactions leading to human development, conservation, management, and development of natural resources in an efficient manner. However, to achieve these goals, further research is required on the following lines:

1. Careful evaluation of various social, economic, environmental, biophysical, and developmental concerns linked with incorporation of trees into AFS and the diversification of existing AFS into new agroecological regions, particularly degraded lands.
2. Integration of environmental services and concerns linked with tree crops with the research and development initiatives to have an ecologically sustainable AFS.
3. Identification, formulation, development, and adoption of new technologies involving native multipurpose tree species keeping in mind the perception and needs of local stakeholders.
4. Developing, evaluating, and promoting innovative synergistic agroforestry technologies that provide multiple environmental benefits in synergism with economic returns.
5. Innovative AFS designs for large-scale biodiversity conservation including birds, animals, and wildlife.
6. Incorporating indigenous knowledge into the existing and future AFS to enhance overall sustainability.

7. Need of rigorous testing for the invasive and weedy nature of a tree species before incorporation into AFS.
8. Development of efficient management plans for potential invasive agroforestry tree species.
9. Selection and promotion of native tree crop species with multipurpose roles to prevent the introduction and spread of potential invasive tree species.
10. Developing strategies and programs to foster a more efficient relationship between researchers, entrepreneurs, and local stakeholders and providing access to agroforestry technology and benefits to all stakeholders.

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2 Tree–Crop Interactions: Lessons from Temperate Alley-Cropping Systems

Shibu Jose, Samuel C. Allen, and P.K. Ramachandran Nair

CONTENTS

2.1 INTRODUCTION

Individuals and institutions in the world's temperate regions are increasingly taking notice of the science and art of alley cropping. This is due in part to growing concerns over the long-term sustainability of intensive monocultural systems. In the temperate context, alley cropping involves the planting of timber, fruit, or nut trees in single or multiple rows on agricultural lands, with crops or forages cultivated in the alleyways (Garrett and McGraw, 2000). Major purposes of this type of agroforestry system include production of tree or wood products along with crops or forage; improvement of crop or forage quality and quantity by enhancement of microclimatic conditions; improved utilization and recycling of soil nutrients for crop or forage use; control of subsurface water levels; and provision of favorable habitats for plant, insect, or animal species beneficial to crops or forage (USDA, 1996; Garrett and McGraw, 2000).

As an association of plant communities, alley cropping is deliberately designed to optimize the use of spatial, temporal, and physical resources by maximizing positive interactions (facilitation) and minimizing negative ones (competition) between trees and crops (Jose et al., 2000a). For example, trees in these systems are capable of improving site-growing conditions for crops in terms of soil and microclimate modification, thus improving productivity (Wei, 1986; Wang and Shogren, 1992). Trees are also capable of capturing and recycling lost soil nutrients (Nair, 1993; Palm, 1995; Rowe et al., 1999), and are thus a potential moderating factor in groundwater pollution caused by leaching of nitrates and phosphates (Williams et al., 1997; Garrett and McGraw, 2000). Trees also provide producers an opportunity to utilize idle growing area during the early stages of tree stand establishment, thus providing a more immediate return on land investment (Williams et al., 1997). Likewise, government incentive programs promote tree planting on private lands (Zinkhan and Mercer, 1997; Garrett and McGraw, 2000). In addition, trees on agricultural lands offer landowners the possibility of accruing carbon credits via the sequestration of stable carbon stock, an added incentive for adopting alley cropping (Dixon, 1995; Williams et al., 1997; Sampson, 2001). Moreover, new technologies for agroforestry modeling, such as the WaNuLCAS (Water, Nutrients, Light Capture in Agroforestry Systems) model (van Noordwijk and Lusiana, 1999, 2000) and the SBELTS (ShelterBELT and Soybeans) model (Qi et al., 2001), are shedding light on the potential for applying agroforestry techniques in new locales. However, trees also compete with plants for available light, water, nutrients, and other resources, which can negatively impact productivity. Thus, more understanding is needed of tree–crop interactions in temperate settings to design agroforestry systems that make best use of the various resources at hand to increase both productivity and sustainability. This is the subject of this chapter.

2.2 ALLEY CROPPING IN THE TEMPERATE REGIONS

Alley cropping, like any other agricultural practice, has been shaped by the environmental and sociocultural contexts in which it has been applied. In the temperate zones, where agriculture has generally been driven by high-input, large-scale production and, more recently, on management for environmental sustainability, alley cropping has naturally tended to mirror these practices. Although much of its foundation has been derived from tropical zone applications, temperate zone alley cropping nevertheless remains a distinct practice. Generally, trees in temperate systems are planted at comparatively wider spacings than those in the tropics, to allow for mechanical cultivation of crops in the strips or alleys (Williams et al., 1997; Gillespie et al., 2000). In addition, temperate systems do not typically rely on the direct reintroduction of prunings from trees or shrubs to maintain soil fertility and productivity (Garrett and McGraw, 2000). To provide a better understanding of temperate alley cropping, we first examine how it is practiced in various regions of the world.

In the mid-western United States and parts of Canada (e.g., Ontario), many of the alley-cropping systems in use are based on the production of high-value hardwoods (Garrett and McGraw, 2000). Perhaps the most widely planted species in such systems is black walnut (*Juglans nigra* L.) (Williams et al., 1997; Garrett and McGraw, 2000; Jose et al., 2000a). Companion crops that are typically grown with black walnut include winter wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and forage grasses. Black walnut systems have been useful in shedding light on various biophysical parameters, including water and nutrient competition, crop productivity, and crop response to juglone, an allelopathic compound (Williams et al., 1997; Jose and Gillespie, 1998; Garrett and McGraw, 2000; Jose et al., 2000a).

Fruit and nut production are also important components of alley cropping in various parts of North America. For example, in southern Canada, producers are growing vegetables and other crops among their fruit and nut trees during orchard establishment (Williams and Gordon, 1992). For example, peach (*Prunus persica* L.) trees have been intercropped with tomatoes (*Lycopersicon* spp.), pumpkins (*Cucurbitaceae* spp.), strawberries (*Fragaria* spp.), sweet corn (*Z. mays* L. var. *rugosa* Bonaf.), and other vegetables. Similarly, chestnut (*Castanea* spp.) trees have been intercropped with soybeans, squash (*Cucurbitaceae* spp.), and rye (*Secale cereale* L. subsp. *cereale*) (Williams and Gordon, 1992). Other species such as red oak (*Quercus rubra* L.), Norway spruce

(*Picea abies* L. Karrst.), White ash (*Fraxinus americana* L.), White cedar (*Chamaecyparis thyoides* L.), Red maple (*Acer rubrum* L.), and Carolina poplar (*Populus canadensis* Moench.) have been intercropped with soybeans, corn, and barley (Williams and Gordon, 1992).

Systems involving softwood production are more important in the southern United States and have involved silvopastoral systems for cattle grazing, and alley-cropping systems for forage production (Mosher, 1984; Zinkhan and Mercer, 1997). Pine species such as loblolly pine (*Pinus taeda* L.), longleaf pine (*P. palustris* Mill.), and slash pine (*P. elliottii* Engl.) have been intercropped with forage crops such as crimson clover (*Trifolium incarnatum* L.), subterranean clover (*T. subterraneum* L.), ryegrass (*Lolium perenne* L.), bahiagrass (*Paspalum notatum* Flugge.), coastal Bermuda grass (*Cynodon dactylon* L. Pers.), tall fescue (*Festuca arundinacea* Schreb.), and other species (Davis and Johnson, 1984; Clason, 1995; Morris and Clason, 1997; Zinkhan and Mercer, 1997). Pines have also been intercropped with row crops such as cotton (*Gossypium* spp.), peanuts (*Arachis hypogaea* L.), soybean, corn, wheat, and watermelon (*Citrullus lanatus* Thumb. Monsaf.) (Zinkhan and Mercer, 1997; Allen et al., 2001; Ramsey and Jose, 2001). Pecan (*Carya illinoensis* L.), an important nut-bearing species, has been intercropped with soybeans, grains, squash, potatoes (*Solanum tuberosum* L.), peaches, raspberries (*Rubus* spp.), and other crops (Nair, 1993; Williams et al., 1997; Zinkhan and Mercer, 1997; Cannon, 1999; Long and Nair, 1999; Reid, 1999; Ramsey and Jose, 2001).

Other species of current or potential application to North American alley cropping include trees such as honeylocust (*Gleditsia triacanthos* L.), basswood (*Tilia* sp.), silver maple (*Acer saccharinum* L.), oak (*Quercus* spp.), ash (*Fraxinus* spp.), poplar (*Populus* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), and black locust (*Robinia pseudoacacia* L.), as well as speciality crops such as ginseng (*Panax quinquefolium* L.) and goldenseal (*Hydrastis canadensis* L.) (Garrett and McGraw, 2000; Miller and Pallardy, 2001).

In temperate regions of South America (e.g., southern Chile and Argentina), silvopastoral systems are a prevalent form of agroforestry. These may involve tree species such as Radiata pine (*Pinus radiata* D. Don.), nire (*Nothofagus antarctica* G. Foster Oerst.), and lenga (*N. pumilio* Poepp. & Endl. Krasser) (Somlo et al., 1997; Amiotti et al., 2000). Such species may be intercropped with forage grasses or legumes such as subclover (Balocchi and Phillips, 1997).

Alley cropping in the Australian or New Zealand sector has tended to focus on large-scale timber production with forage production and grazing of sheep or cattle underneath (Mosher, 1984; Hawke and Knowles, 1997; Moore and Bird, 1997). Common tree species in these systems include Radiata pine and various eucalypts (e.g., *Eucalyptus accedens* W. Fitzg., *E. globulus* Labill., *E. maculata* Hook, *E. saligna* Sm.), and forage grasses include ryegrass, white clover (*Trifolium* spp.), and other species (Hawke and Knowles, 1997; Moore and Bird, 1997). Planting of poplar with row and vegetable crops has also been reported in Australia (Garrett and McGraw, 2000).

Various systems have also been developed in Europe over the years. English walnut (*Juglans regia* L.), for example, is a common species for intercropping systems, which might include alfalfa or forage grasses (Dupraz et al., 1998; Mary et al., 1998; Paris et al., 1998; Pini et al., 1999). In addition, poplar has been grown with vegetable and row crops, as reported for the former Yugoslavia area (FAO, 1980; Garrett and McGraw, 2000). Another tree–crop combination of scientific interest is hazel (*Corylus avellana* L.), interplanted with cocksfoot (*Dactylis glomerata* L.) (de Montard et al., 1999). Lastly, forest grazing, an ancient silvopastoral system in which thinned stands of species such as Scots pine (*P. sylvestris* L.) and European larch (*Larix decidua* Mill.) are oversown with grasses and grazed by sheep and cattle, is also reported to be in use in various parts of Europe (Dupraz and Newman, 1997).

Agroforestry is also popular in China, and its practice dates back many centuries (Wu and Zhu, 1997). Various types of intercropping systems are in use today, with biomass and nut–tree intercropping systems being common. Intercropping systems based on paulownia (*Paulownia* spp.), a fast-growing species, are popular (Wu and Zhu, 1997). Scientific study of this species has focused on paulownia–winter wheat intercrops in north central China (Chirko et al., 1996). Planting of poplar with vegetable and row crops has also been reported in China (Kai-fu et al., 1990; Garrett and McGraw, 2000).

Alley cropping is also practiced in the mid-elevation regions of the Himalaya mountains of India, with fruit trees and other species (Nair, 1993). For example, citrus is grown with gram (*Cicer arietinum*) and winter vegetables, and beans and peas are grown under dwarf-apple (*Pyrus* sp.), peach, plum (*Prunus domestica* L.), apricot (*P. armeniaca* L.), and nectarine (*P. persica* L.) (Tejwani, 1987; Nair, 1993). These and other systems point to the uniqueness and complexity of tree–crop interactions in each geographic location.

2.3 INTERACTIONS BETWEEN TREES AND CROPS

A guiding principle of agroforestry is that productivity can increase if trees capture resources that are underutilized by crops (Cannell et al., 1996). Thus, alley cropping may be viewed as a complex series of tree–crop interactions guided by utilization of light, water, soil, and nutrients. An understanding of the biophysical processes and mechanisms involved in the mutual utilization of these resources is essential for the development of ecologically sound agroforestry systems (Ong et al., 1996). The following section discusses important above- and belowground interactions occurring between trees and crops in temperate alley-cropping systems.

2.3.1 Aboveground Interactions

2.3.1.1 Light Availability, Competition, and Facilitation

Light is the major aboveground factor affecting photosynthesis and biological yields within agroforestry systems. Trees and crops capture light in the form of photosynthetically active radiation, or PAR (400–700 nm wavelength). The degree of light capture is dependent on the fraction of incident PAR that each species intercepts and the efficiency with which the intercepted radiation is converted by photosynthesis (Ong et al., 1996). These factors, in turn, are influenced by time of day, temperature, CO_2 level, species combination, canopy structure, plant age and height, leaf area and angle, and transmission and reflectance traits of the canopy (Brenner, 1996; Garrett and McGraw, 2000).

The effect of light interception on biological productivity has been widely studied (e.g., Monteith et al., 1991; Monteith, 1994; Chirko et al., 1996; de Montard et al., 1999; Gillespie et al., 2000). When water or nutrients are not limiting factors, biomass production may be limited by the amount of PAR that tree and crop foliage can intercept (Monteith et al., 1991; Monteith, 1994). Chirko et al. (1996), for example, in their study of a *Paulownia*–winter wheat intercropping system in northern China found that low PAR levels resulting from overhead shading significantly reduced yield of winter wheat near tree rows (Figure 2.1). However, they also found that, with a wide interrow spacing, late leaf flush, north–south tree arrangement, and long clear boles, wheat was able to receive higher levels of PAR in the morning and afternoon. Lin et al. (1999), in a greenhouse experiment on the effects of shade on forage crop production, found that shading significantly reduced the mean dry weights (MDW) of various warm-season grasses and legumes (Table 2.1).

On the other hand, studies have pointed to minimally negative or even positive effects (facilitation) of moderate shading on crop growth in some cases. In theory, crop photosynthesis levels may remain unchanged under shade, provided that the understory species becomes "light saturated" at relatively low levels of radiation (Wallace, 1996). Lin et al. (1999), in the same greenhouse study cited earlier, found that 50% shading did not significantly reduce MDW of cool-season grasses. Interestingly, two native warm-seasons legumes, Hoary Tick-clover and Panicled Tick-clover, exhibited shade tolerance and had significantly higher MDW at 50% and 80% shade than in full sunlight (Lin et al., 1999; Garrett and McGraw, 2000). These authors also reported that total crude protein content of some of the forage species was greater under 50% and 80% shade than in full sun (Table 2.2). It is likely that shading has caused a reduction in cell size, thereby concentrating nitrogen content per cell as speculated by Kephart and Buxton (1993).

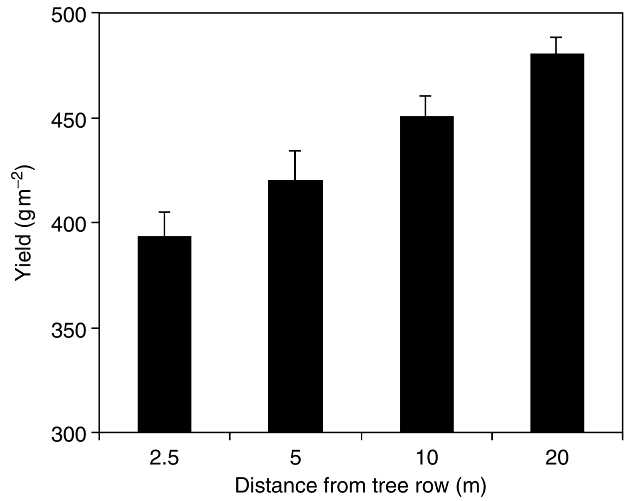

FIGURE 2.1 Winter wheat grain yield as influenced by distance from the tree row in a *Paulownia*–winter wheat alley-cropping system in northern China. (Adapted from Chirko, C.P., M.A. Gold, P.V. Nguyen and J.P. Jiang, *For. Ecol. Manage.*, 83, 171, 1996.)

Research by Jose (1997) and Gillespie et al. (2000) indicated that shading did not have a major influence on the yield of maize in two mid-western United States alley-cropping systems with black walnut and red oak. These researchers found that, in general, the eastern-most row of maize in the black walnut alley cropping received 11% lower PAR than the middle row (Figure 2.2). Shading was greater in the red oak alley cropping because of higher canopy leaf area, where a 41% reduction was observed for the eastern row. Similarly, western rows were receiving 17% and 41% lower PAR than the middle rows in the black walnut and red oak systems, respectively. Irrespective of the shading, no apparent yield reduction was observed when belowground competition for nutrients and water was eliminated through trenching and polyethylene barriers.

2.3.1.2 Microclimate Modification

The presence of trees in an alley-cropping system modifies site microclimate in terms of temperature, relative humidity, and wind speed, among other factors. Figure 2.3 summarizes the microclimatic modifications that occur when trees are introduced into an agricultural field. Serving as windbreaks, trees slow the movement of air and thus in general promote cooler, moister site conditions. Temperature reductions in the alleys can help to reduce heat stress of crops by lowering rates of foliar evapotranspiration and soil evaporation. Together, these factors have a moderating effect on site microclimate.

Crops such as cotton and soybean have higher rates of field emergence when grown at moderate outdoor temperatures. For example, Ramsey and Jose (2001), in their study of a pecan–cotton alley-cropping system in northwest Florida, observed earlier germination and higher survival rate of cotton under pecan canopy cover, due to cooler and moister soil conditions. Similarly, a study in Nebraska showed earlier germination, accelerated growth, and increased yields of tomato (*Lycopersicon esculentum* L.) and snap bean (*Phaseolus vulgaris* L.) under simulated narrow alleys compared with wider alleys (Bagley, 1964; Garrett and McGraw, 2000). In addition, studies on *Paulownia*–wheat intercropping in temperate China showed increased wheat quality due to enhanced microclimatic conditions (Wang and Shogren, 1992). Wind speed was also substantially reduced under a Radiata pine silvopastoral system in New Zealand due to increased tree stocking (Hawke and Wedderburn, 1994).

TABLE 2.1
Total Aboveground Dry Weight of 30 Forages under Three Levels of Shade during 1994 and 1995 at New Franklin, Missouri, U.S.A.

Species	Scientific Name	Full Sun (g)	50% Shade (g)	80% Shade (g)
Introduced cool-season grasses				
Kentucky bluegrass	*Poa pratensis* L.	12.5 a	12.3 a	8.0 b
Orchardgrass "Benchmark"	*Dactylis glomerata* L.	13.8 a	11.7 a	6.4 b
Orchardgrass "Justus"	*Dactylis glomerata* L.	11.7 a	11.2 a	9.5 a
Ryegrass "Manhattan II"	*Lolium perenne* L.	12.7 a	11.1 ab	8.6 b
Smooth bromegrass	*Bromus inermis* Leyss.	9.6 a	12.0 a	9.5 b
Tall Fescue "KY31"	*Festuca arundinacea* Schreb.	13.3 a	16.2 a	8.0 b
Tall Fescue "Martin"	*Festuca arundinacea* Schreb.	12.4 a	11.8 a	6.0 b
Timothy	*Phleum pratense* L.	10.2 a	9.0 a	5.5 b
Introduced warm-season grasses				
Bermuda grass	*Cynodon dactylon* (L.) Pers.	56.1 a	37.0 b	8.6 c
Native warm-season grasses				
Big Bluestem	*Andropogon gerardii* Vitman	45.3 a	33.4 b	17.8 c
Buffalograss	*Buchloe dactyloides* (Nutt.) Engelm.	29.9 a	13.7 b	6.1 b
Indiangrass	*Sorghastrum nutans* (L.) Nash	42.3 a	30.2 b	16.9 c
Switchgrass	*Panicum virgatum* L.	79.5 a	57.6 b	26.5 c
Introduced cool-season legumes				
Alfalfa "Cody"	*Medicago sativa* L.	6.2 a	5.3 ab	3.8 b
Alfalfa "Vernal"	*Medicago sativa* L.	9.4 a	7.1 b	4.2 c
Alsike clover	*Trifolium hybridum* L.	17.0 a	9.8 b	5.4 c
Berseem clover	*Trifolium alexandrinum* L.	16.0 a	7.0 b	2.9 c
Birdsfoot trefoil hybrid "Rhizomatous"	*Lotus corniculatus* L.	15.0 a	9.8 b	5.3 c
Birdsfoot trefoil "Nocern"	*Lotus corniculatus* L.	19.6 a	12.6 b	6.0 c
White clover	*Trifolium repens*	16.0 a	13.0 a	9.5 b
Red clover	*Trifolium pratense* L.	19.9 a	12.1 b	5.9 c
Introduced warm-season legumes				
Korean lespedeza	*Kummerowia stipulacea* (Maxim.) Mankino	42.7 a	29.7 b	13.5 c
Korean lespedeza "Summit"	*Kummerowia stipulacea* (Maxim.) Mankino	34.1 a	12.7 b	7.3 c
Striate lespedeza "Kobe"	*Kummerowia striata* (Thumb.) Schindler	28.5 a	23.6 a	14.7 b
Serecia lespedeza	*Lespedeza virginica* L.	55.9 a	37.9 b	24.6 c
Native warm-season legumes				
Hoary Tick-clover	*Desmodium canescens* L.	16.8 b	22.2 a	21.9 a
Panicled Tick-clover	*Desmodium paniculatum* L.	21.0 b	26.2 a	23.0 ab
Hog peanut (overwintered)	*Amphicarpaea bracteata* L.	8.8 b	28.9 a	31.0 a
Slender lespedeza (overwintered)	*Lespedeza virginica* L.	18.7 a	19.4 a	9.6 a

Source: Adapted from Lin, C.H., R.L. McGraw, M.F. George, and H.E. Garrett, *Agroforestry Syst.*, 44, 109, 1999.

Note: Means followed by the same letter within a row do not differ significantly from each other (Tukey's studentized range test, $\alpha = 0.05$).

TABLE 2.2
Percent Crude Protein (CP%) and Total Crude Protein/Pot (TCP) of Selected Grasses and Legumes When Grown under Three Levels of Shade during 1994 and 1995 at New Franklin, Missouri, U.S.A.

	CP%			TCP (g)		
Species	**Full Sun**	**50% Shade**	**80% Shade**	**Full Sun**	**50% Shade**	**80% Shade**
Introduced cool-season grasses						
Kentucky bluegrass	20.3 b	20.7 b	22.7 a	2.45 A	2.58 A	1.57 B
Orchardgrass "Benchmark"	12.6 c	15.7 b	19.6 a	1.80 A	1.84 A	1.19 B
Orchardgrass "Justus"	19.8 a	16.7 a	18.5 a	1.60 A	1.92 A	1.79 A
Ryegrass "Manhattan II"	15.3 b	16.0 b	18.5 a	1.74 A	2.06 A	1.62 A
Smooth bromegrass	16.7 c	18.1 b	20.2 a	1.64 A	2.25 A	1.94 AB
Tall Fescue "KY31"	14.0 b	15.0 b	18.1 a	1.83 B	2.43 A	1.43 C
Tall Fescue "Martin"	14.3 b	15.5 b	18.5 a	1.75 A	1.84 A	1.12 B
Timothy	15.4 c	17.6 b	20.4 a	1.60 A	1.59 A	1.12 A
Introduced cool-season legumes						
Alfalfa "Cody"	19.4 a	19.9 a	19.4 a	1.49 A	1.48 A	1.00 A
White clover	20.1 a	20.6 a	19.9 a	2.49 A	2.03 A	1.23 B
Introduced warm-season legumes						
Striate lespedeza "Kobe"	13.2 a	13.0 a	12.5 a	3.34 A	2.65 B	1.56 C
Native warm-season legumes						
Slender lespedeza	11.0 a	10.5 a	10.8 a	2.04 A	2.04 A	1.04 A
Panicled Tick-clover	11.6 b	11.7 b	12.9 a	2.57 B	3.53 A	3.38 A
Hoary Tick-clover	13.0 a	13.2 a	12.8 a	2.19 B	2.98 A	2.88 A
Hog peanut	9.1 ab	8.7 b	9.7 a	0.80 B	2.51 A	2.97 A

Source: Adapted from Lin, C.H., R.L. McGraw, M.F. George, and H.E. Garrett, *Agroforestry Syst.*, 53, 269, 2001.

Note: Means followed by the same letter within a row do not differ significantly from each other (Tukey's studentized range test, $\alpha = 0.05$).

2.3.1.3 Weed Density

The presence of a tree canopy alters the growing environment for any species that may find its way into the understory, including weeds. The abundance of weed species in the environment ensures that some species will likely invade an intercropped area, and, through natural selection, adapt to the spectrum of existing growing conditions present. Generally, this condition results in a change in weed density or weed species composition, depending on distance from tree component. Ramsey and Jose (2001), in their study of a mature pecan–cotton intercrop in Florida, observed that, unlike monocrop plots, plots under pecan trees were heavily infested with Asiatic dayflower (*Commelina communis* L.), an exotic, summer annual that appeared to be shade loving. The presence of this weed was attributed to the nutrient-rich soil of the understory, as well as the moist conditions of the soil due to shading. In this case, weeds (e.g., Bermuda grass) that were prevalent in the cotton monoculture were less prevalent within the alleys of the intercrop due to niche specificity.

2.3.1.4 Insect Density

Plant–insect interactions are another important factor in the design of agroforestry systems, as variations in tree–crop combinations and spatial arrangements have been shown to have an effect on insect population density (Vandermeer, 1989; Altieri, 1991; Nair, 1993). According to Stamps and Linit (1997), agroforestry is a potentially useful technology for reducing pest problems because tree–crop combinations provide greater niche diversity and complexity than polycultural systems of

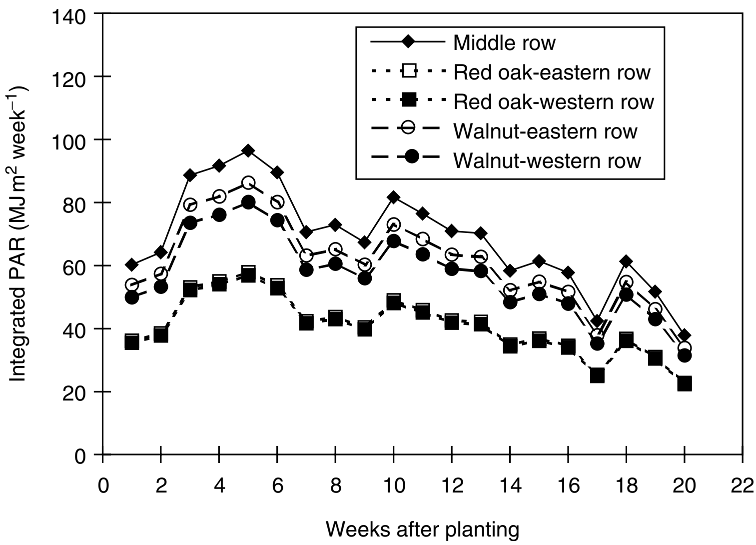

FIGURE 2.2 Seasonal variation in weekly incident PAR (June 1 through October 15, 1996) at three different locations (eastern row, middle row, and western row) in black walnut and red oak alley-cropping systems in mid-western United States. (Adapted from Jose, S., *Interspecific Interactions in Alley Cropping: The Physiology and Biogeochemistry*, Ph.D. Dissertation, Purdue University, West Lafayette, IN, 1997.)

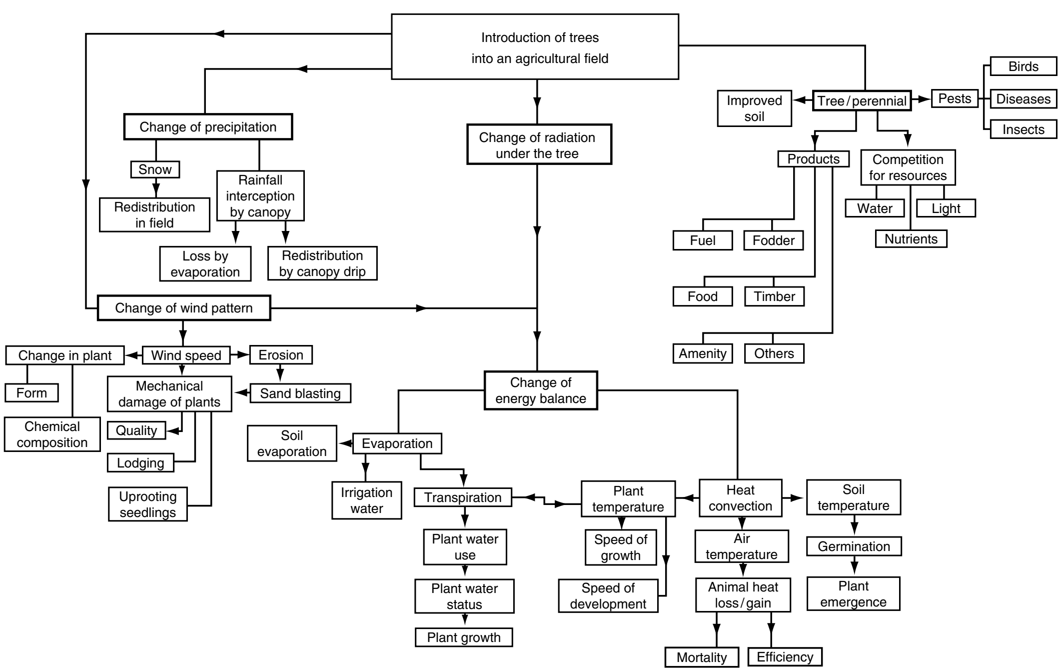

FIGURE 2.3 The changes in a predominantly agricultural-based landscape following introduction of trees. The flow diagram shows causal relationships by lines with arrows and subdivisions by lines without arrows. (From Brenner, A.J., *Tree-Crop Interactions: A Physiological Approach*, C.K. Ong and P. Huxley, eds., CAB International, Wallingford, UK, 1996. With permission.)

annual crops. This effect may be explained in one or more of the following ways: (1) wide spacing of host plants in the intercropping scheme may make the plants more difficult to find by herbivores; (2) one plant species may serve as a trap-crop to detour herbivores from finding the other crop; (3) one plant species may serve as a repellent to the pest; (4) one plant species may serve to disrupt the ability of the pest to efficiently attack its intended host; and (5) the intercropping situation may attract more predators and parasites than monocultures, thus reducing pest density through predation and parasitism (Root, 1973; Vandermeer, 1989).

Various studies have shed light on plant–insect interactions. Studies with pecan, for example, have looked at the influence of ground covers on arthropod densities in tree–crop systems (Bugg et al., 1991; Smith et al., 1996). Bugg et al. (1991) observed that cover crops (e.g., annual legumes and grasses) sustained lady beetles (*Coleoptera: Coccinellidae*) and other arthropods that may be useful in the biological control of pests in pecan (Bugg et al., 1991; Garrett and McGraw, 2000). However, Smith et al. (1996) found that ground cover had little influence on the type or density of arthropods present in pecan. Although beyond the scope of this discussion, the competitive activity of belowground pests is another important consideration (Ong et al., 1991).

2.3.2 Belowground Interactions

2.3.2.1 Soil Structure Modification

Trees play an important role in soil structure and subsequent soil-holding capacity. The presence of trees on farmlands can improve the physical conditions of the soil—permeability, aggregate stability, water-holding capacity, and soil temperature regimes—the net effect of which is a better medium for plant growth (Figure 2.3; Nair, 1987). In addition, various factors work to protect soil from the damaging effects of rain and wind erosion. Tree canopies, for example, intercept and rechannel rainfall and wind in patterns that tend to be less damaging to soil (del Castillo et al., 1994). Ground-level physical barriers in the form of stems, roots, and litterfall also help to protect the soil from surface runoff (Kang, 1993; del Castillo et al., 1994; Sanchez, 1995; Garrett and McGraw, 2000). Further, agroforestry systems can add significant amounts of organic matter to the soil, which can aid in providing cover as well as improving soil physical and chemical properties. In a recent study, Seiter et al. (1999) demonstrated that soil organic matter could increase by 4%–7% in alley-cropping systems with red alder (*Alnus rubra* Bong.) and maize in comparison with maize monoculture following 4 years of cropping (Figure 2.4). The presence of abundant organic matter serves to reduce soil compaction and increase infiltration and porosity (del Castillo et al., 1994). The net effect of soil structure modification is reflected in the degree to which roots are able to permeate the soil and exploit water and nutrient resource pools.

2.3.2.2 Water Availability, Competition, and Facilitation

Water is a major limiting factor in plant growth and productivity. The presence of trees in an agricultural system alters the soil water availability of the system, with repercussions for all associated plants. Trees generally have deeper roots and a higher fine root biomass than crop plants, and thus are in a more favorable position for water uptake than neighboring crops (Jose et al., 2000a). Fine roots are generally concentrated in the top 30 cm of the soil, where water fluctuation is greatest (Nissen et al., 1999; Gillespie et al., 2000; Jose et al., 2000a, 2000b) and severe water and nutrient competition takes place (Rao et al., 1993; Lehmann et al., 1998). In some cases, trees and crops may utilize separate soil water resource pools due to differences in rooting depth and intensity (Wanvestraut et al., 2004). However, in many cases, trees and crops compete directly for water. When this happens, soil water availability tends to be lower for the associated agronomic or forage crop due to competitive disadvantages in water acquisition (Rao et al., 1998; Jose et al., 2000a). Ultimately, the impact of soil moisture depletion on crops is expressed in terms of lower emergence rate, diminished plant size, and decreased yield (Jose et al., 2000a).