Advances in Agroforestry

Volume 4

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Aims and Scope

Agroforestry, the purposeful growing of trees and crops in interacting combinations, began to attain prominence in the late 1970s, when the international scientific community embraced its potentials in the tropics and recognized it as a practice in search of science. During the 1990s, the relevance of agroforestry for solving problems related to deterioration of family farms, increased soil erosion, surface and ground water pollution, and decreased biodiversity was recognized in the industrialized nations too. Thus, agroforestry is now receiving increasing attention as a sustainable land-management option the world over because of its ecological, economic, and social attributes. Consequently, the knowledge-base of agroforestry is being expanded at a rapid rate as illustrated by the increasing number and quality of scientific publications of various forms on different aspects of agroforestry.

Making full and efficient use of this upsurge in scientific agroforestry is both a challenge and an opportunity to the agroforestry scientific community. In order to help prepare themselves better for facing the challenge and seizing the opportunity, agoroforestry scientists need access to synthesized information on multi-dimensional aspects of scientific agroforesty.

The aim of this new book-series, *Advances in Agroforestry*, is to offer state-of-the art synthesis of research results and evaluations relating to different aspects of agroforestry. Its scope is broad enough to encompass any and all aspects of agroforestry research and development. Contributions are welcome as well as solicited from competent authors on any aspect of agroforestry. Volumes in the series will consist of reference books, subject-specific monographs, peer-reviewed publications out of conferences, comprehensive evaluations of specific projects, and other book-length compilations of scientific and professional merit and relevance to the science and practice of agroforestry worldwide.

The titles published in this series are listed at the end of this volume.

Shibu Jose • Andrew M. Gordon
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Toward Agroforestry Design

An Ecological Approach

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ISBN 978-1-4020-6571-2 e-ISBN 978-1-4020-6572-9

Library of Congress Control Number: 2007936553

Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

springer.com

Preface

Ecology and its underlying principles have not received much attention in the agroforestry research and development arena despite its pivotal role in determining the biological sustainability of agroforestry systems. Although often acknowledged, ecological principles are seldom explored in many of the world's best developed and well-known agroforestry systems. However, it is worth noting that this trend is slowly changing as we recognize that agroforestry systems, if not designed based on sound ecological principles, are unable to attain their fullest potential. In fact, the last 5 years have seen an exponential increase in journal articles and synthesis work that explore the ecological foundations of global agroforestry practices.

The idea for the current book originated following the 1st World Congress of Agroforestry, Orlando, FL, USA, June–July, 2004. We, the editors of this book, had organized two sessions, both focused on the ecological basis for designing agroforestry systems. Invited and voluntary papers and posters were presented in these sessions which represented a cross-section of the current global biophysical research being conducted in a variety of agroforestry systems. Dr. P.K.R. Nair, the Chair of the Organizing Committee of the 1st World Congress of Agroforestry, encouraged us to consider publishing an edited volume in the new book series, Advances in Agroforestry, for which he serves as the series editor. We accepted his advice enthusiastically and immediately started working on the project. Selected authors were invited to submit manuscripts for peer review; we subsequently went through a rigorous peer review process that resulted in the acceptance of 14 manuscripts for the current volume.

The manuscripts represent a mix of original research and synthesis work from both tropical and temperate regions of the world. We have grouped them into five sections. The first section that consists of one chapter is an introduction to the role of ecological knowledge in agroforestry design. The second section has eight chapters that explore the resource allocation patterns and aboveground processes in various agroforestry systems. The four chapters included in the third section deal with resource allocation patterns with respect to belowground processes, while recent advances in analytical and modeling tools are explored in the fourth section. The final section is a chapter that synthesizes the current state of knowledge with respect to ecological knowledge in agroforestry systems.

We are grateful to a large number of individuals for their assistance in accomplishing this task. We would like to express our sincere gratitude to Dr. P.K.R. Nair for his continued support and encouragement throughout the publication process. In addition, we thank the authors for their long and continued commitment to this project. The invaluable comments and suggestions made by the referees also significantly improved the clarity and content of the chapters. In addition to many of the authors who served as reviewers for other chapters, we thank: Samuel Allen, Kent Apostol, Michael Bannister, Tamara Benjamin, David Burner, Barry Brecke, James Burger, Wendell Cropper, Stanley Gathumbi, Rico Gazal, Michael Gold, James Jones, Ole Hendrickson, Robert Kalmbacher, Andy Kenney, John Kort, Peter Nkedi-Kizza, Kye-Han Lee, Ofelia Plascencia, James Quashie-Sam, Meka Rao, Phil Reynolds, Michelle Schoeneberger, Johannes Scholberg, Richard Schultz, Dennis Shannon, Jamie Simpson, Daniel Stephenson, Naresh Thevathasan, and Vic Timmer for their help in reviewing manuscripts. We also wish to extend our sincere thanks to Catherine Cotton and her staff at Springer Science for their timely efforts in publishing this book.

June, 2007

Shibu Jose
Andrew M. Gordon

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Introduction

Chapter 1
Ecological Knowledge and Agroforestry Design: An Introduction

S. Jose[1,*] and A.M. Gordon[2]

Introduction

Agroforestry is receiving long overdue attention as an alternative land-use practice that is resource efficient and environmentally friendly. Multiple outputs and the flexibility of having several options for management make agroforestry an attractive alternative to conventional agriculture and forestry for landowners in many parts of both temperate and tropical regions of the world.

Although design of these integrated tree–crop and/or tree–crop–livestock systems can be flexible in order to meet the different objectives or constraints of farmers or landowners, there are many obstacles, in both ecological and economic terms, to overcome to make them attractive to landowners. The acceptability of agroforestry systems by landowners would be improved if interactions that exist between trees, crops, and/or livestock remain largely beneficial so that productivity per unit area of land is increased while reducing environmental risks associated with monocultural systems. However, this is not an easy task. These multistoried, multicomponent systems are more complex than single-species cropping systems, and exhibit great variety in temporal and spatial ecological interactions; in fact, a number of positive and negative interactions have been postulated between different components of these systems. In a biological context, the success of such a complex system will depend on minimizing the negative interactions associated with forcing crops (animals or plants) and trees to grow together spatially while enhancing the synergistic interactions between system components.

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Agroforestry Design

It is well known that the practice of mixing of trees, crops, and livestock has been in existence for millennia. The impetus for agroforestry practices lies in the harmonious existence of many species in natural forested ecosystems that yielded multiple products, and in the need for historical societies with rising populations to grow tree and food products on a limited land base. Modern agroforestry concepts and paradigms evolved with the complex natural mixtures in mind, although many of the agroforestry systems that are seen today throughout the world have only a few component species. Yet, the design and management of these systems remain challenging because of a lack of understanding of the nature of interactions among components that ultimately drive system productivity and sustainability.

Depending upon the type of practice, agroforestry design can involve working with a number of components. However, four key criteria characterize and distinguish agroforestry practices from others as given below (Gold et al., 2000):

1. *Intentional*: combinations of trees, crops and/or livestock are intentionally designed, established, and/or managed to work together and yield multiple products and benefits.
2. *Intensive*: agroforestry systems are created and intensively managed to maintain their productive and protective functions and interactions and often involve cultural operations such as cultivation, fertilization, irrigation, pruning, and thinning.
3. *Integrated*: components are structurally and functionally combined into a single integrated management unit so that the productive capacity of the land is fully utilized.
4. *Interactive*: agroforestry systems actively manipulate and utilize the biophysical interactions among component species for optimal yield of multiple products or ecosystem services.

Ecological Approach

The underlying principles of agroforestry systems can be traced back to the more complex natural systems from which they evolved. Olson et al. (2000) outlined four general ecological principles that are common to complex natural systems, but of particular interest in designing agroforestry systems. They are:

1. *Ecosystems are distinguished by spatial and temporal heterogeneity*: An ecosystem or landscape consist of a mosaic of patches and linear components. The boundaries or edges between patches or the interface of different habitat are often the sites of increased rates of processes such as nutrient and energy exchange, competition, facilitation, and movement of organisms. In agroforestry system design, the interface between the woody and non-woody components deserves special attention. Optimizing the positive interactions at the interface is critical in ensuring the sustainability of the system. Temporal variability such as phenology can also be taken into account in designing agroforestry systems. For example, both Jose et al. (2000) and Allen et al. (2004) observed a temporal separation in nitrogen uptake of the tree and crop components of temperate alley-cropping systems, alleviating direct competition for nitrogen between system components.
2. *Disturbance is a primary determinant of ecosystem structure and function*: Ecosystems constantly change in ways that are only partially predictable. As described by Vogl (1983) "when a living thing, community or system ceases to change, it is nonfunctioning, decadent, or dead". Natural systems are dynamic systems, forever changing in response to successional forces, long-term fluctuations in climate, and the more immediate effects of natural disturbance from disease, drought, fire, insects, storms, and the movements of earth, wind, and water. Integrating the principles of disturbance ecology into sustainable agroforestry management practices has received considerable attention in the recent past. For example, the use of fire in silvopastoral systems to stimulate forage productivity or thinning the tree component in order to regulate shading patterns in alley cropping or multistrata systems have become routine management practices in many parts of the world.
3. *Perennialism is the most common condition in natural ecosystems*: Natural systems feature perennials in mixtures rather than annuals in monoculture. Annual plants tend to dominate early in the successional process, but are quickly replaced by perennials. However, repeated disturbance events often provide periodic windows of opportunity for annuals and hence perennials and annuals can coexist at various stages throughout the successional progression of an ecosystem. Agroforestry systems provide many opportunities to introduce perennials to annual cropping systems or annuals to perennial systems depending upon the objective of the landowner.
4. *Structural and functional diversity are important to ecosystem performance, but are difficult to quantify*: When ecosystems consist of species that create structural and functional diversity, resource use efficiency and system productivity are often enhanced. The competitive exclusion principle (Gause's principle) has been central to explaining the coexistence of species in mixtures for decades (Grime, 1973). It states that different species having identical ecological niches cannot exist for long in the same habitat. In other words, stable coexistence of two species is only possible where intraspecific competition is greater than interspecific competition for both species. In agroforestry systems, structural and functional diversity are increased by mixing the component species. As a result they are able to coexist and increase the overall resource use efficiency of the system.

As one reads through the chapters of this book, it becomes quickly apparent that we have come a long way in improving our understanding of the ecological intricacies that define the sustainability and productivity of agroforestry systems the world over. Although we may agree or disagree on how we define agroforestry in a temperate versus tropical context, researchers and practitioners agree that a better understanding of the ecology of agroforestry systems has helped in designing better systems that are resource efficient and sustainable. As pointed out by van Noorwijk et al. (2004), the initial enthusiasm in agroforestry in the early 1970s resulted in a number of "any tree plus any crop" combinations under the umbrella of "agroforestry"; however, many of these mixtures were not yielding the expected benefits normally associated with agroforestry. This led to an increased number of scientific investigations that explored the underlying ecological principles of agroforestry practices. The study of ecological interactions, both above- and belowground, became the focal point of the agroforestry scientific community. It started with tropical agroforestry systems in the 1980s, but soon became commonplace in temperate agroforestry. The advances we have made in our understanding have helped improve the productivity and sustainability of agroforestry systems over that of traditional forms of agroforestry by designing new systems.

The Way Forward

Recent books that cover the fundamental ecological interactions and processes in agroforestry and similar agroecosystems (e.g. Ong and Huxley, 1996; Young, 1997; Huxley, 1999; Ashton and Montagnini, 2000; Vandermeer, 2002; Schroth and Sinclair, 2003; Nair et al., 2004; van Noordwijk et al., 2004) attest to the growing interest in making use of ecological knowledge as an integral part of agroforestry design. Collectively, these references have formed a solid ecological foundation for agroforestry and its way forward. Increasingly, agroforestry systems and practices are being designed by taking local and pertinent ecological knowledge and the landscape context into account. However, as one would expect, past research has made us cognizant of how little we know about the ecology of these systems, especially in the temperate regions. There are more questions than answers and an enormous task lies before us, in terms of dealing with the many challenges of developing appropriate and acceptable agroforestry systems. We need to appreciate the following:

1. *Recognize limited understanding*: Agroforestry systems, whether temperate or tropical, are extraordinarily complex. Most often we extrapolate ecological information from site or specific experiments. We all know we rarely have perfect or complete information for designing or managing agroforestry systems, but need to be cognizant and cautious about the potential limitations and consequences of designing agroforestry systems based on limited knowledge. Adaptive management is the key.
2. *Develop better information*: There is still critical need for site and species specific information on many agroforestry systems from both temperate and tropical regions of the world. Better information on and understanding of the basic ecology of individual species (autecology) and species interactions (community ecology) and species–abiotic interactions (ecosystem ecology) will enhance our ability to make these systems ecologically sustainable. Tactical decisions on management issues will become easier with a solid ecological understanding of the system as a whole.

3. *Develop decision-support tools and models*: Formal guidelines, decision-support tools and process-oriented predictive models can help advance the use of ecological information in a meaningful way in terms of designing and managing new and existing agroforestry systems. Models help us in understanding the relationships among soil, plants, trees, and other components in agroforestry systems, particularly through studying the relationships between system components over time. They are also useful as decision-support tools for identifying best management options for attaining optimal production. We have made some progress in this regard; however, major challenges are still ahead in making these decision-support tools, including making models easily accessible and available for landowners and practitioners.

Outline of the Book

So, the question naturally arises; why another book on agroforestry? We would argue that the book attempts to fill two of the niches that we identified in the earlier discussion (*Develop better information* and *Develop decision-support tools and models*). We intend to complement existing information and syntheses by presenting the latest body of knowledge from a wide variety of agroforestry systems around the globe. We acknowledge that one book alone cannot fill the niches identified earlier. As we advance the ecological science behind agroforestry one study at a time, we will move closer toward making ecological sustainability a global reality for agroforestry systems. We will highlight the chapters included in this book in the following paragraphs.

This book examines a range of issues that can be addressed or ameliorated using agroforestry systems in both a tropical and temperate context, highlights how ecological understanding allows both improved system design and more effective management practices and presents a series of latest developments in improving ecological understanding, including a range of tools for data analysis and modeling.

The eight chapters (Chapters 2–9) included in Section 2 bring together a broad range of examples and draw out underlying principles relating to resource allocation and related ecological processes aboveground. Oelbermann and Gordon, for example, describe the ecological processes in integrated riparian management systems in Chapter 2. The development and design of shelterbelt agroforestry systems and the underlying ecological principles and functions are discussed in detail by Mize et al. in Chapter 3. Forage production in a temperate silvopastoral system and legume cover crop production in a tropical silvopastoral system, both in relation to light intensity, are examined by Feldhake et al. and Baligar et al. in Chapters 4 and 5, respectively. The next two chapters provide examples of how trees modify the microclimate in agroforestry systems using alley cropping as a model system. Zamora et al. (Chapter 6) explains the role of light in determining crop yield in a temperate alley-cropping system and Shapo and Adam (Chapter 6) examine a number of microclimatic parameters in a tropical alley-cropping system in northern

Sudan with respect to their influence on crop yield. The last two chapters deal with resource allocation and use in two Central American agroforestry systems. While Bellow et al. (Chapter 8) explore resource capture and productivity of fruit-based agroforestry systems in highland Guatemala, Vaast et al. (Chapter 9) report on the biophysical interactions that define productivity of coffee under shade trees.

Section 3 has four chapters (Chapters 10–13) that deal with resource allocation and related ecological processes belowground. In Chapter 10, Kiparski and Gillespie explain how the relative importance of below versus aboveground processes shifts as a temperate alley-cropping system involving black walnut (*Juglans nigra*) and maize (*Zea mays*) ages. Gowda and Kumar (Chapter 11) test the hypothesis that root competition in multispecies systems such as homegardens depends on tree traits rather than resource availability. Establishment of *Cordia dodecandra* with *Bixa orellana* on calcareous soils in Yucatan, Mexico under varying degree of water availability is investigated in Chapter 12 by Reuter et al. And finally, in the last chapter (Chapter 13), Mafongoya and Hove synthesize information on the effects of polyphenols on nitrogen use by crops and ruminant livestock, highlighting similarities and differences between crops and livestock systems and discussing the underlying principles of strategies that are available to farmers to improve nitrogen use efficiency.

Section 4 describes important analytical and modeling tools used in agroforestry system design and evaluation. Kimmins et al. examine the role of ecosystem-level models in the design of agroforestry systems in Chapter 14. They describe a family of models based on the hybrid simulation (FORECAST) approach to prediction and scenario analysis. The approach focuses on the combination of experience and process-level understanding as the basis for simulating and evaluating alternative agroforestry designs over various spatial and temporal scales, and the possible consequences of climate change. Measurement and simulation of light availability in a tropical agroforestry system with coffee is the subject of Chapter 15 by Righi et al. and Carrillo and Jordan (Chapter 16) discuss about how the addition of green manure influences the soil community and how this change in turn influences nitrogen mineralization patterns in a temperate alley-cropping system. The above- and belowground interactions with trees and associated crops of *Pennisetum glaucum* and *Sorghum bicolor* are investigated in an agroforestry parkland system in Burkina Faso using the WaNuLCAS model in Chapter 17 by Bayala et al.

Finally, Section 5 provides an overview of the current state of ecological knowledge that is useful in designing agroforestry systems. Further, it identifies existing gaps in our knowledge base and outlines a collaborative approach that is necessary to strengthen the ecological research in agroforestry.

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Section 2
Resource Allocation in Agroforestry Systems: Aboveground Processes

Chapter 2

Biophysical Changes Resulting from 16 Years of Riparian Forest Rehabilitation: An Example from the Southern Ontario Agricultural Landscape

Maren Oelbermann[1], Andrew M. Gordon[2,*], and Narinder K. Kaushik[2]

Introduction

Stream eutrophication in agricultural areas is common in North America and efforts are currently underway to reverse this process. There has been increasing interest in the use of riparian plantings to mitigate eutrophication and to enhance soil and water conservation (Nakao and Sohngen, 2000). In southern Ontario, streamside plantings, apart from conserving soil and water, may also provide tax benefits (under certain programs) in addition to providing short- and long-term woody biomass for on-farm use. Planting fast-growing hybrid poplar as a source of biofuel, for example, may make reforestation of streamsides an attractive financial proposition (Simpson et al. 1993). Reforestation of land along waterways may also compensate for losses of woodland as a result of increasing urban sprawl (Countryman and Murrow, 2000).

Numerous other benefits are derived from riparian plantings. For example, yields of forest plantations on stream banks adjacent to heavily fertilized agricultural land may be higher than those established on traditional planting sites because of the possible uptake of leached inorganic nutrients for tree growth (O'Neill and Gordon, 1994). Riparian plantations will also help to conserve soil by controlling wind and surface erosion (Nakao and Sohngen, 2000).

Riparian forests, adjacent to agricultural fields, could also reduce nutrient loadings to waterways via tree nutrient uptake. This process is enhanced and of great ecological significance if the trees are harvested periodically (e.g. Maki, 2001) ensuring a net uptake of nutrients. If trees are not removed, nutrients that have been taken up by

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trees from adjacent agricultural fields are returned annually to the stream or the soil via litterfall. Many streams adjacent to fields under intense agricultural practice receive high levels of nitrate-nitrogen (NO_3^--N). However, if sufficient organic matter is stored in stream bottom sediments, NO_3^--N can be reduced in stream waters through denitrification (Martin et al. 1999a). The organic matter substrate for this microbial process is provided by riparian vegetation through autumnal litterfall. Denitrification in the riparian buffer community also occurs as a result of an active microbial population in the high quality soil environment (Martin et al. 1999b).

Riparian plantings rehabilitate stream ecosystems by enhancing salmonid and other fish populations. Summer temperatures in waterways draining agricultural landscapes in southern Ontario may climb to temperatures greater than 22 °C (Gordon and Kaushik, 1987); these warm waters generally support, if at all, only marginal populations of the more valuable and environmentally sensitive fish species such as brook trout (*Salvelinus fontinalis* Mitchill). Lower water temperatures, as a result of shade from riparian plantings, could benefit established trout populations and/or allow for the introduction of other fish species (Naiman and Dećamps, 1997). Organic matter entering the stream ecosystem, via litterfall, also provides a source of food for macroinvertebrates and hence, fish (Sweeney, 1993).

Catchment disturbance as a result of deforestation of riparian zones may be temporary. Sweeney (1993) suggests that if riparian forests are re-established within a few years of deforestation, autochthonous primary production decreases rapidly as allochthonous inputs of leaf litter begin to increase. This shift in trophic structure results in the recovery of stream macroinvertebrate communities to near pre-disturbance levels.

Many studies have looked at the effects of riparian forest removal on stream quality (e.g. Bormann and Likens, 1979). More recently, the importance of riparian plantings in agricultural landscapes has been realized and guidelines with respect to buffer width, to trap sediments, have been suggested (Lowrance et al. 2000; Lee et al. 2000). However, the effect of riparian management systems on nutrients and pesticides moving in groundwater beneath buffers has been discussed only in limited and idealized hydrogeologic settings (Simpkins et al. 2002). Management strategies and growth and yield guidelines for riparian plantations in agricultural landscapes also need further investigation. Additionally, little information exists on the reversal of declining stream quality that may be expected from reforesting the banks of degraded streams in agricultural landscapes.

Currently, research indicates that higher organic nitrogen (N) inputs to streams are possible with wider buffers as a result of higher litterfall (Oelbermann and Gordon, 2000). However, these organic inputs may coincide with decreased amounts of inorganic N inputs, because of increased absorption by tree roots in the groundwater pathway or increased denitrification in riparian soils. It is as of yet unclear how rapidly streams will respond to the nature (organic versus inorganic) of N inputs reminiscent of historical times.

One of the first rehabilitation studies in southern Ontario, Canada, occurred at Washington Creek, a stream degraded by many years of poor agricultural practices. The study was initiated in 1985 and hypothesized that reforestation of the stream bank and the riparian zone with fast-growing hardwood tree species would result in improved fish habitat and potential riparian timber plantations. The objectives were first, to evaluate the growth potential, success, and nutrient interception of different tree species planted along the banks of degraded streams, and second, to monitor the changes in fish and invertebrate insect biomass and production that were expected to occur as trees matured and crowns closed over the stream.

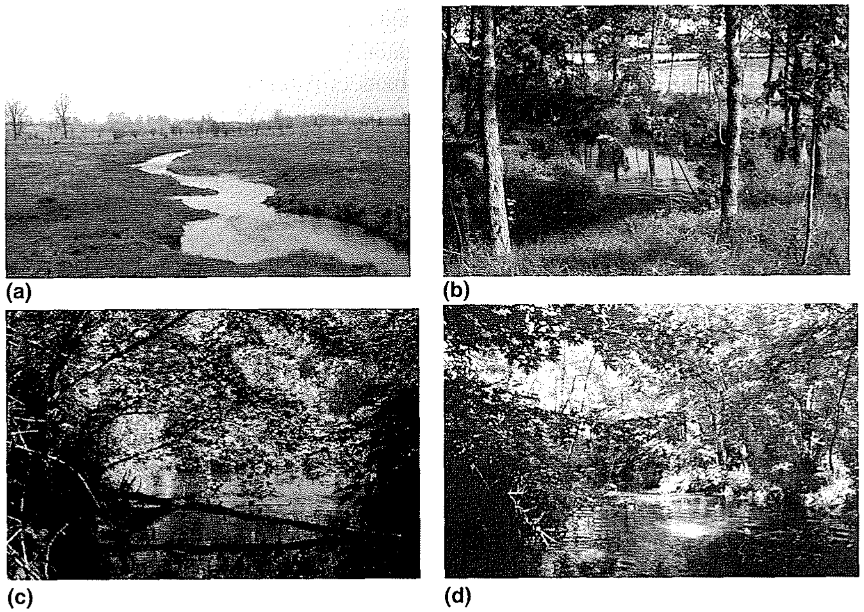

Figure 2.1 Washington Creek, southern Ontario, Canada showing changes in the landscape as a result of riparian rehabilitation. The photos are taken at the same site, which was under pasture before rehabilitation began, over a 16-year period. Photo (a) shows the site prior to rehabilitation activities in 1985; (b) after 50% thinning for biomass data in 1989; (c) in 1995; and (d) in 2001

The objective of this paper is to illustrate changes monitored over a 16-year period in the aquatic and adjacent terrestrial ecosystems of Washington Creek (Figure 2.1), using before and after comparisons. Results described focus on changes in the physical (solar radiation fluxes and sedimentation) and biological environment (litterfall, nutrient fluxes, organic matter retention, and bird, benthic insect, and fish species diversity) of Washington Creek.

Historical Perspectives

Washington Creek is a 9 km long spring-fed first order stream located in Oxford County, an agriculturally dominated landscape in southern Ontario. The stream enters the Nith River (within the Grand River watershed) south of Plattsville

(43≡18′N, 80≡33′Ω) and is typical of agriculturally degraded streams in the region surrounded by cropped fields and pasture, a general lack of riparian vegetation, and areas with a high degree of stream bank erosion where animals (e.g. cattle) have access to sections of the water. The physiography of Oxford County is characterized by sandy hills and kames. Soil parent material of the drainage basin is glacial till (Pleistocene) overlying limestone bedrock (Silurian). Oxford County soils have a loam texture but local hilly areas consist of silt loam and sand (Wicklund and Richards, 1961). Soils of the Washington Creek study site are classified as silt loams (pH = 7.1; $CaCO_3$ = 6.2%) with an organic matter and N content of 7.1% and 0.4%, respectively. The depth of the plow layer was variable and the high organic matter content likely reflects a greater amount of soil from the Ap horizon.

The stream itself is alkaline in nature with pH ranging from 7.5 to 8.5, similar to other rivers within the Grand River watershed. The electrical conductivity of streamwater indicated moderate amounts of dissolved minerals within the stream resulting from the underlying dolomitic limestone formation and soils with high calcareous content. The streambed substrate is coarse-textured, with high gravel contents typical of a glacial outwash stream, and with stream banks of varying channel gradient.

Oxford County is located in the peninsular region of southern Ontario and has a climate modified by the surrounding Great Lakes. The climate is temperate with hot, humid summers and cold winters, a mean annual frost-free period of 134 days, a mean annual precipitation of 820 mm, and a mean annual temperature of 7.2 °C (Environment Canada, 1997).

In 1985, the stream bank along a 1.6 km section of Washington Creek was planted with a variety of alder [*Alnus incana* subsp. *Rugosa* (Du Roi) R.T. Clausen., *Alnus glutinosa* (L.) Gaertn. and *Alnus rubra* Bong.], and hybrid poplar (*Populus* x *canadensis* Moench) trees. Further tree plantings along the stream bank, with silver maple (*Acer saccharinum* L.), occurred in 1986 and in 1990. Additionally, in 1990 and 1991, plantings of multifloral rosevine (*Rosa multiflora* Thunb.) and red-osier dogwood (*Cornus sericea* subsp. *sericea* L.), which are native to this area, were planted in the riparian zone adjacent to the abovementioned hardwood trees, resulting in a buffer width of 50 m. All trees were planted in 4 rows with 3 × 3 m spacing or planted in three blocks randomly located along the stream bank and within the riparian zone, resulting in a tree density of 3.14 trees m^{-2}.

Along a 250 m interval in the rehabilitated section, 3 m long sections of the streambed were modified by the addition of a mixture of large rocks (25–150 mm diameter) covering the bottom of the streambed from bank to bank (Mallory, 1993). The rocks were large enough to prevent them from moving during flooding events, and were obtained from a nearby quarry to ensure a chemical composition similar to that of the streambed. This rehabilitation activity took place in order to evaluate changes in the benthic community.

A site located 60 m upstream from the rehabilitated area was used as a non-rehabilitated (agricultural land use) control for comparison to the rehabilitated site and was representative of conditions prior to planting efforts. Similarly, a site located 400 m downstream with a planted buffer width of one tree row and a channelized stream morphology was also used as a comparison for some of the studies.

In the summer of 1989, 1990 and 2001, incident solar radiation (Photosynthetic Photon Flux Density – PPFD) was measured at the study site to examine the amount of shading on the stream and the understory provided by riparian plantings. Light levels were compared at the rehabilitated site between understory and midstream locations. Measurements were taken with a LICOR LI170 Quantum-Radiometer/Photometer, approximately 1 m above the water surface and the ground within the riparian zone at three randomly selected locations within the rehabilitated site.

In 1988, depth of the stream sediment was determined at 11 randomly chosen sampling locations within the rehabilitated site and the non-forested control. In 2001, the same locations were used for stream sediment depth measurements as part of a follow-up study. Three samples were taken perpendicular to the streamflow using a modified streambed-coring device similar to the US BMH-53 as described by Guy and Norman (1970). A clear, rigid Plexiglas tube 1.3 m in length, with a beveled collecting edge was used to obtain the sediment depths. To obtain an undisturbed sediment profile, the Plexiglas tube was vertically inserted into the stream bottom approximately 5 cm beyond the coarse textured streambed. The upper end of the tubing was sealed and the collection end of the tubing was covered in order to support the sample and maintain an undisturbed state during removal of the coring devise from the streambed. After removal of the coring device, sediment depths were measured.

Experimental procedures for litterfall and nutrient fluxes are described in Oelbermann and Gordon (2000). Within the rehabilitated site, five litter traps (each 4.5 m^2) were suspended 0.5 m above the stream surface and perpendicular to the stream flow extending over the total width of the stream. Litter was collected biweekly from early October to mid-November in 1996 and 1997. Collected litter was dried, weighed, ground, and analyzed for N, and phosphorus (P), potassium (K), and calcium (Ca) content.

In order to determine the retention of leaf litterfall within the stream channel of the rehabilitated section a leaf transport study was initiated by Oelbermann and Gordon (2001). Leaves were collected in October from the rehabilitated site, air-dried and each leaf, per species, was painted with a different color (see Oelbermann and Gordon, 2001). Three 50 m long replicates were established within the rehabilitated area, and were further subdivided into 5 m increments in order to determine the amount of leaves retained within each section. Dyed leaves, representative of each tree species, were released simultaneously into the stream at the 0 m mark and were collected after 45 min at the 50 m mark. Trapped leaves were collected and separated and counted according to species. An inventory of the number of each leaf species retained occurred within each 5 m subdivision. At each 5 m mark, leaf species, number of leaves, and the retention structure type were noted.

Bird species diversity was determined within four randomly assigned 600 m^2 areas within the rehabilitated, channelized, and non-forested area. Within each area, the number of bird species present was determined over a 4-day period in June and October 1990 and 1995. Benthic insects were collected, sorted, and analyzed on four different occasions from the non-forested area, and in the rehabilitated section where the streambed had been modified with rocks, using a 929 cm^2 Surber sampler. Various fish surveys were conducted on a number of reaches on Washington Creek over a period of 2 decades by the local conservation authority (Grand River Conservation Authority), the Ministry of Natural Resources, the University of Waterloo, and the University of Guelph. The inventories were carried out using a backpack electrofishing unit.

Changes in the Physical Environment

Incident Solar Radiation to Washington Creek

Within 4 years of planting, the fast-growing hybrid poplar selected for rehabilitation purposes at Washington Creek provided a significant amount of shading to the stream and the understory vegetation. By 1989, solar radiation loadings were reduced by 26.7% and by 1990, by 37.6%; in 2001, a reduction of 97.0% in incident solar radiation to the stream was noted. Light levels reaching the understory vegetation in the riparian zone (55.60%) were significantly reduced ($p < 0.05$) compared to levels reaching the stream (26.7%) after 4 years of growth (Table 2.1). Comparatively, after 16 years of growth, incident light reaching understory vegetation was reduced by 92.5%, but was significantly higher ($p < 0.05$) than that reaching the stream (97.0%).

Results suggest that radiation loadings reaching the understory vegetation and the stream are sufficiently reduced and thus may support plant communities adapted to low light conditions. Similarly, the degree of shading may be sufficient to reduce water temperatures and algal growth and, depending upon stream velocity could encourage the development of a diverse freshwater flora and fauna.

Table 2.1 Percentage of solar radiation [measured as percentage of Photosynthetic Photon Flux Density (PPFD)] reaching understory vegetation and midstream locations at Washington Creek, southern Ontario, Canada. Values are expressed as a percentage of full sunlight in open areas receiving 100% solar radiation. Standard errors are given in parentheses

	PPFD (%)		
Location	Sample date		
	1989	1990	2001
Mid-stream[a]	73.3 (4.9)	62.4 (6.02)	3.0 (2.1)
Understory[b]	44.4 (5.2)	43.0 (4.50)	7.5 (5.1)

[a] Values in the midstream location are significantly different between years, and between midstream and understory locations at $p < 0.05$.

[b] Values in the understory location are significantly different between years, and between understory and midstream locations at $p < 0.05$.

Streambed Sedimentation

Historical bank instability resulted in the deposition of soil within the streambed of Washington Creek prior to rehabilitative efforts. Streambed sedimentation is defined as the process of subsistence and deposition of suspended material carried in water, and deposited on the streambed (Malanson, 1996). Streambed sediment depth in 1988 was estimated to be 11.2 (±0.9) cm, although this was not significantly different ($p<0.05$) from that of the non-forested site (10.9 ± 1.4) in 1988. In 1995, a reduction in sediment depth ranging from 5 cm to 10 cm was noted, and measurements in 2001 showed that total sediment depth had declined to 4.3 ± 0.7 cm (Table 2.2).

In the 2001 study, sediment depth decreased with downstream distance. A similar observation was made in 1995 where streambed sediment in this area was substantially reduced in the last 200 m of the stream in the rehabilitated zone; this can likely be attributed to the presence of stabilizing vegetation along the stream bank, which decreased bank erosion and thus sediment input. The input of sediment that is still occurring is likely derived from upstream non-forested areas of Washington Creek where intensive agricultural practices, less than 5 m from the stream edge, continue to take place.

In the rehabilitated zone, the mean streambed sediment depth decreased significantly ($p<0.05$) by 6.9 cm between 1988 and 2001. However, no significant decrease ($p<0.05$) was found for the non-forested site where sediment depth was lowered by only 2.1 cm. Reduced sediment depths in the treatment may be a result of rehabilitation efforts from streamside plantings and streambed modifications that ultimately allowed the formation of a dynamic riffle–pool system not present at the control site. For example, sediment accumulation in riffle areas was significantly lower (3.2 ± 0.9 cm) compared to that found in pools (5.1 ± 0.9 cm).

Other studies have found similar levels of sediment reduction as a result of riparian plantings or vegetative buffer strips. For example, Daniels and Gilliam (1996) noted an 80% reduction of the sediment in vegetated riparian systems. However, Abu-Zreig et al. (2004) showed that the efficiency of sediment reduction and filtration in riparian

Table 2.2 Streambed sediment depth (cm) and organic matter content in 1988 and 2001 in a rehabilitated and no-tree control section of Washington Creek, southern Ontario, Canada. Percent organic matter for 2001 data is based on total organic C content. Standard errors are given in parentheses

Sampling date	Treatment area	Depth (cm)	Organic matter (%)
1988	Rehabilitated	11.2 (0.9)^{a,A}	3.7 (0.4)^{a,A}
	Non-forested Control	10.9 (1.4)^{a,A}	4.1 (0.8)^{a,A}
2001	Rehabilitated	4.3 (0.7)^{a,B}	5.3 (0.5)^{a,A}
	Non-forested Control	8.8 (2.5)^{a,A}	6.8 (0.8)^{b,A}

For treatments (rehabilitated and non-forested control) within years, values followed by the same lowercase letters are not significantly different at $p < 0.05$.

Comparison between years and within treatments (e.g. rehabilitated in 1988 compared to rehabilitated in 2001, and likewise for the non-forested control), values followed by the same uppercase letters are not statistically different at $p < 0.05$.

systems is dependent upon buffer width and the type of vegetation. They found that native (60–96%) and existing (90%) riparian vegetation had the greatest ability to trap sediments compared to planted (57–64%) species such as *Festuca rubra* L. and *Lotus corniculatus* L.

Changes in the Biological Environment

Organic Matter and Nutrient Fluxes

Aboveground litterfall from trees in the rehabilitated section, and in a mature (~150 years) riparian system, was previously reported by (Oelbermann and Gordon, 2000). Litterfall in the rehabilitated site (1161 kg ha^{-1} year^{-1}) was significantly lower ($p < 0.05$) compared to litterfall in the mature riparian zone (3238 kg ha^{-1} year^{-1}) also located in the Grand River watershed. Litterfall fluxes determined at Washington Creek were similar to those reported on in other studies in agricultural landscapes (e.g. De Long and Brusven, 1994) but lower than those associated with mature forest riparian zones (Pozo et al. 1997).

However, nutrient fluxes from litterfall in the rehabilitated site (21.0 kg N ha^{-1} year^{-1}; 2.6 kg P ha^{-1} year^{-1}) were not significantly different ($p < 0.05$) compared to litterfall in the abovementioned mature riparian zone (24.4 kg N ha^{-1} year^{-1}; 3.8 kg P ha^{-1} year^{-1}) (Oelbermann and Gordon, 2000). This suggests that trees at Washington Creek may be intercepting nutrients in agricultural runoff, which would otherwise reach the creek and lower water quality (Table 2.3).

Although no specific studies on nutrient interception by tree species have been undertaken at Washington Creek, several ancillary studies illustrate this potential using tree species commonly planted in riparian zones. Alders, for example, have a high potential for soil improvement and reclamation of degraded land and grow well in riparian zones. The best alder candidates for streamside plantings might be ones exhibiting high inorganic N-uptake rates in conjunction with low autumnal foliar N levels. Gordon and Kaushik (1986) evaluated a variety of *Alnus incana*, *Alnus glutinosa*, and *Alnus rubra* provenances for growth rate and nutrient uptake potential at Washington Creek between 1985 and 1990. A local Ontario *A. incana* source proved to be an excellent candidate with respect to the aforementioned attributes, and appeared to exhibit N-uptake rates in excess of 1.1 g m^{-2} year^{-1}, even at an early stage.

Table 2.3 Annual litterfall and nutrient fluxes, determined from litterfall (leaves and branches), at Washington Creek compared to a mature (~150 years) riparian zone (for N and P fluxes only) in southern Ontario, Canada. Standard errors are given in parentheses

Litterfall and nutrient flux to the stream	Treatment area	1996 (kg ha^{-1} year^{-1})	1997 (kg ha^{-1} year^{-1})
Litterfall[a]	Rehabilitated	1504 (299)	1717 (334)
	Mature riparian zone	–	3238 (61)[b]
N[a]	Rehabilitated	20.2 (5.2)	21.0 (3.6)
	Mature riparian zone	–	24.4 (4.9)[a]
P[b]	Rehabilitated	–	2.6 (0.4)[a]
	Mature riparian zone	–	3.8 (0.5)[a]
K[b]	Rehabilitated	9.4 (2.2)	6.6 (1.1)
Ca[b]	Rehabilitated	41.1 (7.5)	31.3 (4.5)

[a] Data taken from Oelbermann and Gordon (2000).

[b] Data taken from Oelbermann (1999).

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O'Neill and Gordon (1994) determined N interception by roots of Carolina poplar growing in artificial riparian zones. They found that trees just 1 m in height and planted at densities of either 1 or 2 trees per 0.48 m^2 filtered 11% and 14%, respectively, more NO_3^--N than zones containing no trees. They also examined tree roots and found a significant increase in root biomass and N content with increasing NO_3^--N application rates. Both of these studies, in concert with litterfall nutrient data lend credence to the idea that riparian forests may significantly impact the quantity and quality (organic versus inorganic) of the nutrient load entering streams from adjacent terrestrial areas. Studies by Martin et al. (1999b), Meals and Hopkins (2002), Lee et al. (2003), and Mckergow et al. (2003) also showed large reductions in NO_3-N and PO_4-P within the riparian zone.

Organic Matter Transport and Retention

Transport of organic matter within the stream channel is defined as the amount of detritus exported from the stream, whereas retention reflects the availability of food resources for aquatic biota (Lamberti and Gregory, 1996). Retention includes both the immediate (active) trapping of organic matter and the long-term (passive) storage of this material. Several studies have determined stream organic matter retention within the stream channel in undisturbed forest ecosystems (e.g. Lamberti and Ehrman, 1992; Jones, 1997). However, limited data exists on organic matter retention in reforested riparian zones although this information could provide further insight into which tree species are most suitable for rehabilitation purposes in terms of maximizing detrital retention.

In 1998, a leaf transport and retention study was initiated in the rehabilitated zone at Washington Creek (Oelbermann and Gordon, 2001). The study found a significant difference ($p < 0.05$) in the number of leaves retained within the stream channel in the rehabilitated (54.6%) area compared to a channelized (49.3%) section. Results suggested that the determining factor for leaf retention was stream morphology, including the degree of meandering, water velocity, and streambed width and depth, rather than buffer width.

The study by Oelbermann and Gordon (2001) found that approximately 30% of the leaves were retained within the first 10 m of the stream in the rehabilitated site, whereas the same proportion of leaves was retained over a distance of 30 m in the channelized area of Washington Creek. A significantly higher ($p < 0.05$) number of silver maple (30%) leaves were retained compared to poplar leaves (15%). However, no difference was found between alder and poplar leaves, and is likely a function of similar leaf morphologies between the two tree species. Leaves were trapped on various physical structures within the stream in the following order: rocks > stream bank > complete channel obstructions (debris dams) > tree roots > woody material (Oelbermann and Gordon, 2001).

Bird Diversity

The impact of the riparian plantings on bird populations was assessed in 1990 and 1995 and results showed that a higher number of bird species were nesting and foraging in the rehabilitated area. In 1990, bird species diversity was greater in the rehabilitated area and lowest in the channelized and the non-forested control site (Table 2.4). A follow-up survey in the autumn of 1995 showed that a higher number of birds, including blue jays (*Cyanocitta cristata* L.), song sparrows (*Melospiza melodia* Wilson), black-capped chickadee (*Parus atricapillus* L.), cedar waxwings (*Bombycilla cedrorum* Vieillot), and yellow-rumped warblers (*Dendroica coronata* L.), were found in the rehabilitated area compared to the channelized and non-forested areas.

It is likely that birds used the rehabilitated area as a resting place, as part of their migratory behavior in the autumn, resulting in higher bird diversity because the rehabilitated riparian zone provided greater habitat diversity and shelter compared to the other areas. For example, Pierce et al. (2001) surveyed two shelterbelt agroforestry systems in Nebraska and found that the percent of woody cover was a significant determinant of bird species richness.

Benthic Insect and Fish Diversity

Modification of the streambed by the addition of gravel resulted in changes to the creek's substratum and influenced benthic insect populations. Insect abundance per square meter was significantly greater ($p < 0.05$) in the treatment areas ($7640\,m^{-2}$)

Table 2.4 Total number of bird species observed nesting and foraging in 1990 in four different treatment areas at Washington Creek, southern Ontario, Canada. The Shannon Index of Diversity is also presented

	Number of species		
Treatment area	Nesting	Foraging	Shannon Index
Wide buffer	10.1^{a}	19.2^{a}	0.8767
Channelized	2.5^{b}	10.2^{b}	0.4771
Non-forested control	2.5^{b}	10.0^{b}	0.4680

For the number of bird species, within columns (nesting and foraging), numbers followed by the same lowercase letters are not significantly different at $p < 0.05$.

compared to the non-forested control ($4021\,m^{-2}$) (Mallory, 1993). This suggests that substrate enhancement, in association with other aspects of rehabilitation, may mitigate negative processes associated with adjacent agricultural practices.

Numerous fish inventories have been conducted over a 25-year period along various reaches of Washington Creek. These surveys have indicated little differences between the rehabilitated and non-forested control sites with respect to the number of species on any given sampling date.

However, some interesting differences in species composition between the rehabilitated and non-forested control sites should be noted. For example, in 1987 red-sided dace (*Clinostomus elongates* L.), classified as a provincially rare fish species in Ontario, were recorded in the rehabilitated section, and since 1989, a resident brook trout population has been observed in the rehabilitated zone. The last fish survey at Washington Creek, including the rehabilitated site, took place in October 2000. Results indicated a high abundance of white sucker (*Moxostoma anisurum* Rafinesque), blacknose dace (*Rhinichthys atratulus* Hermann), creek chub (*Semotilus atromaculatus* Mitchill), and common shiner (*Notropis cornutus* Mitchill) in the rehabilitated area in addition to the resident brook trout population (J. Wright, 2000, personal communication).

One of the goals of riparian zone conservation is linked to the potential of streamside vegetation to lower water temperatures, and to improve water quality for fish, particular salmonids. The average historical maximum temperature at Washington Creek (~25 °C) suggests that its waters are marginal for sustaining a brook trout community. However, the establishment of a resident brook trout population since 1989 suggests that conditions within the rehabilitated site have likely become more favorable for that species. A number of factors may have contributed to this, including the possible changes in food availability, a decrease in sediment depth, lowered agricultural runoff, increased shading resulting in reduced stream temperatures in deeper pools, increased bank cover, and increased habitat diversity in the riparian zone.

Conclusions

In southern Ontario, the removal of streamside vegetation, in order to increase agricultural production, has resulted in the degradation of streams causing poor water quality, soil erosion, stream sedimentation, elevated stream temperatures, and a loss of wildlife habitat. Rehabilitation of these degraded landscapes may mitigate some of these negative effects. At Washington Creek, results from a variety of studies over 16 years have illustrated a range of changes in the biophysical and biological environment as a consequence of riparian rehabilitation.

In southern Ontario, non-point source pollution and degraded waterways continue to be a problem in agricultural landscapes. Efforts are currently underway in the United States and to a lesser extent in Canada to institute riparian plantings to improve soil and water quality. Studies in the United States have shown that riparian plantings can be economically viable for controlling soil erosion if monetary subsidies are provided (Countryman and Murrow, 2000; Nakao and Sohngen, 2000).

Initiating riparian plantings is particularly effective on land with low crop yields or land low in value (Countryman and Murrow, 2000). Riparian plantings can also be of interest to those with long-term investment objectives, when economically valuable tree species such as black walnut (*Juglans nigra* L.), sugar maple (*Acer saccharum* Marsh.), or red oak (*Quercus rubra* L.) are used for reforestation. Streamside forests may also act as a corridor for connecting isolated wooded areas in fragmented agricultural, suburban and urban landscapes, offering additional woodland habitat and dispersal routes.

The Washington Creek study was one of the first attempts in North America to document long-term changes, resulting from rehabilitative efforts on streams, using riparian plantations. Although this study took place over 16 years, it is estimated that complete rehabilitation, including reproducing vegetation and improved water quality, may take at least 30 years (Howard-Williams and Pickmere, 1993).

As such, further studies addressing water quality issues including groundwater dynamics and nutrient uptake by streamside plantings are warranted for the assessment of biotic communities in riparian zones in agricultural landscapes. It is especially important to address these issues in already established riparian plantings in order to follow long-term changes. Additionally, short-term studies using a variety of tree species in riparian plantings are also needed in order to determine the type of vegetation that will provide maximum benefits for soil, water and wildlife conservation.

Acknowledgments We thank the Ontario Ministry of Agriculture and Food (OMAF) for providing funding for the initial rehabilitation project. We would also like to thank the Brethren of Early Christianity for granting access to Washington Creek and the Grand River Conservation Authority for updated fish surveys. We thank James Simpson and Don Hamilton for technical support, and Michael Ormston-Holloway for field assistance.

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Chapter 3
Ecological Development and Function of Shelterbelts in Temperate North America

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Introduction

As the world's population continues to expand, the pressure on farmland, both from expansion of urban areas (United Nations, 2002) and from a need to produce more food and fiber (Hewitt and Smith, 1995; Gardner, 1996), will increase. In direct competition with the increasing demand for more food and fiber is a growing public desire for conservation of natural systems and a focus on quality of life issues (Matson et al., 1997; Jackson and Jackson, 2002; Pimentel et al., 2004).

These two societal needs are clearly linked. Unfortunately, they are antagonistic, not complementary. The impacts of intensive agriculture, needed to increase food and fiber production, extend well beyond the field border (CAST, 1999). Similarly, many species found in natural systems, both flora and fauna, do not remain within protected reserves provided for their benefit and are impacted by land-use decisions in surrounding areas. A challenge to resource managers is to develop management strategies that support both sets of needs and lead to the "right compromise" between production agriculture, sustainability, and conservation of native floral and fauna (Mineau and McLaughlin, 1996; Swift et al., 2004).

Shelterbelts and other types of linear forest systems, such as riparian buffer strips (Benton et al., 2003), can support both sets of needs and be a link between production agriculture and protection of biodiversity. These systems, both planted and naturally occurring, provide various ecosystem services (Guertin et al., 1997). While this review focuses on shelterbelts, many of the principles discussed apply to other linear forest systems.

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

Shelterbelts, linear arrays of trees and shrubs planted to create a range of benefits, are a major category of agroforestry practices (Buck et al., 1999). Shelterbelts have been managed for centuries to alter environmental conditions in agricultural situations and recently have been used in rural/urban interfaces, providing numerous economic, social, and environmental benefits (Droze, 1977; Cook and Cable, 1995; Schoeneberger et al., 2001). Shelterbelts are called by different names (windbreaks, hedgerows, fence rows), depending upon their use, region, or preference of the individual. For simplicity we have chosen to use the terms interchangeably.

Shelterbelts produce a variety of economic benefits. They protect crop fields by reducing wind erosion, improving crop water use and increasing crop yields and economic returns (Kort, 1988). They protect livestock from harsh winter conditions, reducing animal stress and improving animal health. In addition, they reduce feed requirements, which reduces input costs and increases profits (Dronen, 1988). Around farm buildings they protect living and working areas, making outside work less stressful (Wight, 1988), and they reduce air exchange rates in buildings, which reduces heating and cooling costs (DeWalle and Heisler, 1988). Living snow fences can be used to manage drifting snow. Dense shelterbelts trap snow close to the shelterbelt, reducing snow removal costs from adjacent roadways and improving road safety (Shaw, 1988). Porous field shelterbelts alter windflow so that snow is distributed relatively uniformly across a field, providing critical soil moisture for next year's crop (Scholten, 1988). Urban shelterbelts are used at the rural/urban interface to provide many of the previously described services (Josiah et al., 1999), as well as serving as visual and odor barriers (Schoeneberger et al., 2001). Cook and Cable (1995) describe shelterbelts as designed corridors that add scenic beauty to agricultural landscapes. These benefits and others are well documented in numerous original articles and are summarized in a number of comprehensive reviews (Brandle et al., 1988, 2000, 2004; Burke, 1998; Caborn, 1957, 1971; Grace, 1977; Cleugh et al., 2002).

In addition to the many direct economic benefits of shelterbelts, there are numerous environmental impacts, both positive and negative, that result from shelterbelt technology. Although not easily quantified, these environmental responses often have economic implications. Issues related to wildlife habitat and biodiversity serve as examples of the difficulty in quantifying the economic value of shelterbelts. Shelterbelts provide critical habitats for many species in areas dominated by large monoculture fields of agricultural crops, which, although difficult to assign a value, is a positive value for society, but shelterbelts also provide travel corridors for encroachment of undesirable plant and animal species, which represents a difficult to assign negative value to individual landowners and society (Forman, 1995). Shelterbelts can attract bird species that feed on crop pests, reducing insecticide requirements and costs (Trinka et al., 1990; Dix et al., 1995), but they also can attract flocks of bird species that feed on crops, reducing yield and profit (Johnson and Beck, 1988; Bollinger and Caslick, 1985). Predators, including humans, recognize the advantages of hunting along a shelterbelt (Cable and Cook, 1990). Predator–prey relationships of crop pests and natural predators may be influenced, positively or negatively, by the availability of overwintering habitat (Slosser and Boring, 1980).

Control of wind and water erosion by systems of shelterbelts has far reaching consequences on the offsite costs associated with erosion, including air and water quality, which impact human health (Huszar and Piper, 1986; Williams and Young, 1999). These social and environmental effects clearly have economic values, but the values are difficult to assign with the size and direction (positive or negative) of the value often dependent on the individual.

All of these impacts arise from shelterbelt technology. The ecological role and function of shelterbelts, which produce a range of benefits and problems, are the subjects of this review. The review starts with a discussion of the three phases of a shelterbelt's life cycle: establishment, functional, and mature/senescent. Following that, the ecological functions of a shelterbelt as a corridor and the implications for management are discussed. Although shelterbelts are composed of trees and/or shrubs, we will, for simplicity, only refer to trees during the discussion. In most cases when we mention trees, it should be read as trees and shrubs.

Establishment Phase

The establishment phase begins with site preparation in the year prior to planting and lasts for 5–10 years, depending upon the growth rate of the species and overall growing conditions. Shelterbelts are usually established on agricultural lands, either crop fields or pastures. For crop fields, there often is no site preparation other than cultivation after the final harvest. For pastures, site preparation often involves using herbicides to kill all vegetation in the entire shelterbelt zone – the land occupied by the shelterbelt – or to kill 1–2 m wide strips into which trees will be planted. Sometimes cultivation, alone or after herbicide application, is used for site preparation of pastures. Typical site preparation results in a clean cultivated strip of bare soil or a strip of dead grass into which trees will be planted (Ritchie, 1988; Schroeder, 1988). The ecological consequences of site preparation are minimal outside of the shelterbelt zone.

As shelterbelts are generally planted into agricultural soils that usually have abundant soil seed banks (Leck et al., 1989), the shelterbelt zone can be quickly populated by annual and perennial plants, creating a diverse stand in early stages of succession. Such vegetation can shade seedlings and transpire considerable quantities of soil moisture, which will negatively affect survival and growth of a newly planted shelterbelt. As a result, weed control is an important management tool for shelterbelt establishment (Schroeder, 1988). Effective weed control reduces competition for moisture, nutrients, and light and generally results in high seedling survival and good seedling growth (Ritchie, 1988).

Each weed control technique will create different site conditions and thus different habitats for both plant and animal species. With complete weed control the microenvironment of newly planted shelterbelts tends to be hotter and drier than surrounding areas. Litter accumulation and plant diversity are minimal. Habitat niches are few, and use by wildlife is generally low (Yahner, 1983a, b). With less complete weed control, more weeds develop, and the microenvironment changes. This increases the habitat value for birds, small mammals, and insects and may result in slowed tree growth (Schroeder, 1988) and increased animal damage to young seedlings (Timm, 1988).

There are two approaches to control weeds with herbicides in newly planted shelterbelts: pre-emergents and post-emergents. Pre-emergents produce essentially bare soil, while post-emergents result in soil covered with a small amount of dead weeds. When either technique is effectively applied, the shelterbelt zone remains relatively weed free (Woeste et al., 2005).

Weed control using cultivation affects the vegetation, soil structure, and microorganisms associated with surface layers (Brady and Weil, 2000). Cultivation may add organic matter by incorporating weeds, but it also increases oxidation of soil organic matter (Lai et al., 1997). Cultivation increases evaporation from the soil surface and leads to loss of soil moisture in the shelterbelt zone.

Mowing is a commonly used, although not particularly effective, form of weed control (Schroeder, 1988). While preventing weeds from competing with trees for light, mowing does little to reduce moisture competition and can stimulate weed growth. Mowing strongly influences the species composition of weeds, favoring grass species that are well adapted to mowing, which can be very competitive with trees when mowing is stopped. Mowing reduces cover, which makes the shelterbelt zone less desirable as wildlife habitat. Reduced cover exposes rodents to predation by raptors, which often leads to reduced damage to newly planted trees. On sites where erosion is a potential problem, mowing leaves the soil protected while partially controlling weeds (Read, 1964).

Controlling weeds with mulches is probably the most environmentally safe way to provide weed control (Stepanek et al., 2002). Mulches may be inorganic, such as plastics or landscape fabrics, or organic, such as wood chips, straw, or hay. The ecological impacts of each type depend on the specific type of mulch used. Black plastic mulch controls weeds but is impervious to water and raises soil temperature (Hodges and Brandle, 1996). The color of plastic mulch affects reflectance from the surface and soil temperatures, which influences root growth (Appleton et al., 1990). Woven black fabric mulches are a better alternative, allowing water to enter the soil profile while controlling weeds. Trees respond positively to both materials.

Using organic mulches (basically litter) will add organic matter to soil, but may reduce available nitrogen if incorporated into the soil (Borland, 1990; Gouin, 1992). Organic mulches improve soil structure and serve as a food source for microorganisms. In contrast to plastic mulch, organic mulches act as insulation and reduce soil temperature fluctuations. In temperate regions of North America this usually means an increase in root activity and growth, especially in the summer and fall. At more northern latitudes (e.g. in the boreal forest region) or at high elevations (alpine systems) lower soil temperatures in the spring may delay root growth and reduce overall tree height (Lahti et al., 2005; Landhausser et al., 2001). In some cases, however, root growth may be shallow, occurring primarily in the litter or mulch layer, decreasing the ability of roots to tap deeper water resources and potentially increasing susceptibility to extended drought periods (Stuckey, 1961; Watson, 1988).

The type of organic mulch can be critical. Grass or crop residue mulches break down quickly and need to be replenished on a regular basis. A layer of larger bark or wood chips, 8–12 cm deep will last 3–5 years. Mulching with grass or crop residue tends to favor small rodents, which may result in girdling of trees. Mulching with larger pieces of bark or wood chips reduces the impact of rodent populations (Borland and Weinstein, 1989).

In some areas, trees are irrigated until they are well established. Using drip irrigation may encourage localized root systems and lead to reduced root biomass (Klepper, 1991), leaving a large tree with an unfavorable root to shoot ratio when the water source is removed, i.e. the root system may be too small to support the aboveground portion (Romero et al., 2004). Sprinkle irrigation applies water to the entire shelterbelt zone, leading to additional weed competition and potentially to reduced tree growth.

During the establishment phase, the trees in a shelterbelt develop from small seedlings to trees that are 3–5 m tall. Individual trees are clearly evident at the beginning of the establishment period but will begin to grow together by the end of the period. Spacing between trees determines how soon closure occurs and influences the degree of competition between trees and the amount of radiation reaching the surface. If spacing and weed control are adequate, trees will have crowns that extend from the top of the tree to near the ground. Consequently, shelterbelt trees tend to have a very different morphology from most forest grown trees. Forest grown trees often grow in more crowded conditions, which results in shading and death of lower branches and individual trees. For a given soil and climate, forest grown trees will tend to be taller, have shorter crowns and smaller diameters than comparably aged shelterbelt trees (Zhou et al., 2002; 2005). Unlike forest grown trees, shelterbelt trees retain their lower branches due to the linear nature of the planting and the greater availability of radiation.

Spacing between trees within the row varies with design objective and local site conditions, but in general, spacings of 2–5 m for most tree species and 1–2 m for most shrub species are typical. Closer spacings reduce the time necessary for development of a barrier or until canopy closure but may shorten the overall life span of the windbreak. In contrast, wider spacings increase the length of time required to form a barrier and increase the life span of the shelterbelt.

In either case, as the canopy closes and the barrier forms, light penetration into a shelterbelt decreases. In multiple row shelterbelts, interior branches begin to die back, similar to a forest situation but remain an important part of overall windbreak structure until they abscise (Brandle et al., 2004). Branch death is affected by the shade tolerance of the tree species and spacing of the trees (Kozlowski and Pallardy, 1997).

Initially, biodiversity in the shelterbelt zone is controlled by what is planted and the extent and type of weed control. Most shelterbelts are composed of several species (2–5), but sometimes will be a single species and occasionally more than five species. Depending upon the level of weed control, this low level of diversity may be retained for 5–10 years. More routinely, weed control is not perfect, and numerous herbaceous species will become established within the shelterbelt zone. Most will originate from the soil seed bank, but others will be blown in by wind or carried in by birds or small mammals. These species will be typical weeds of the local area, including both annual and perennial grasses and broadleaf species. With these weeds will come associated insects and their predators (Dix and Leatherman, 1988; Showler and Greenberg, 2003; Wilson et al., 2004).

The abundance and species composition of the understory will change over time, due to decreasing light levels and increasing moisture competition from trees. As the shelterbelt grows, shade-intolerant species will be replaced with more shade-tolerant species (Hiller, 2004; Sutton, 1992). The understory can be ideal habitat for certain wildlife species and can provide numerous niches for various types of insects (Pasek, 1988). As the understory and tree canopy develop, a litter layer will form, and soil microorganisms occupying the site will change to reflect the changing soil conditions. The formation of a barrier affects windflow, and plant material from adjacent fields may collect in the shelterbelt zone, adding to the litter under the shelterbelt (Johnson and Beck, 1988).

In the typical monoculture field of annual crops, a shelterbelt in the first several years of establishment provides minimal habitat for most wildlife. By the end of the establishment phase, some birds, primarily edge species or generalists, will begin to utilize shelterbelt trees for nesting and for perches (Yahner, 1982; Jobin et al., 2001). As this occurs, seeds from other areas will be carried in and become established in the understory (McArthur and McArthur, 1961). As the understory continues to develop, rodents and other small mammals may begin to utilize the windbreak (Yahner, 1983b; Timm, 1988).

A few thoughts on shelterbelt species selection are in order at this time. Obviously, the species chosen for a shelterbelt will have a large role in determining the ecological impact of the shelterbelt. Soil and climate conditions are usually the most limiting environmental factors in species selection, but other factors, such as landowner preferences and local regulations, may also influence species choice.

Native species are usually best because they are adapted to the growing conditions of the area. There are, however, a number of introduced species that have been used successfully in shelterbelts throughout North America. For example, within the Great Plains region, native conifer species are limited and several European pine species, notably *Pinus sylvestris* and *P. nigra*, are naturalized and used widely. In contrast, most regions have an adequate number of native hardwood species for use in shelterbelts.

Genera, such as spruce (*Picea* spp.) and cedar (either *Juniperus* spp. or *Thuja* spp.), produce dense shade, limiting understory vegetation. Pine (*Pinus* spp.) produces moderate shade, while deciduous species generally produce light to moderate shade depending on canopy structure (Larcher, 1995).

Species composition of a shelterbelt determines the nature of the litter layer, which along with canopy structure, influences understory species composition and use by various insect and small mammal species.

Regardless of the species chosen, each species or group of species has a specific growth form which helps determine shelterbelt structure. Similarly, canopy structure influences windflow and light climate in and around the shelterbelt zone. A single row of conifers will have a very different structure than a single row of deciduous hardwoods (Brandle et al., 2004). Similarly, spacing between trees will influence structure, for example, trees planted on a 2 m spacing will create a different canopy structure than those on a 3 m or 4 m spacing. And multiple row shelterbelts produce an entirely different understory microenvironment than a single row shelterbelt. Most of these differences are minor during the establishment phase, especially early in the establishment phase. As a shelterbelt matures and canopy structure becomes more defined, initial species composition plays a larger row in determining conditions within and around the shelterbelt zone (Heisler and DeWalle, 1988; Zhou et al., 2002, 2005).

Functional Phase

At the transition from establishment to functional phase, crowns of the developing shelterbelt trees will begin to touch, forming a barrier that increases in height with age. Individual trees begin to compete for space, light, moisture, and nutrients. As in a typical forest situation, those species and individuals with the best genetics will be able to most efficiently utilize the resources of the site. But unlike a forest in which the species and individuals that most efficiently utilize resources become dominant, trees in shelterbelts are spaced so that all have adequate space to survive and the potential to develop into large trees. However, like the forest, shelterbelt trees will vary in size, depending on their individual genetics and ability to compete. In addition, soil variations across the landscape will influence tree growth. As the number of rows in the shelterbelt increases, the shelterbelt responds more like a forest. While individual tree growth and survival are important, it is the structure of the shelterbelt as a barrier to windflow that is generally the most important characteristic of a successful shelterbelt (Wang et al., 2001; Zhou et al., 2005).

Shelterbelt structure determines the amount of wind speed reduction that occurs in the vicinity of a shelterbelt. As a result of changes in wind speed and turbulence created by a shelterbelt, microclimate within the sheltered area is altered. In general, exchange rates between the atmosphere and soil and plant surfaces are reduced, and as a result, average daily temperature and humidity are increased slightly in the sheltered area. Detailed discussions of the microclimatic impacts of shelterbelts and the crop responses to these changes have been presented elsewhere (McNaughton, 1988; Brandle et al., 2000, 2004) and are not repeated here. Our focus remains on development of a shelterbelt and its ecological impacts in the shelterbelt zone and within the agroecosystem at the landscape scale.

For single row shelterbelts, canopy structure and shelterbelt orientation are the primary factors determining the light climate near the shelterbelt. For east–west oriented shelterbelts, the north side of the shelterbelt receives primarily diffuse light and will have a lower total radiation load than the south side. On the south exposure, radiation reflected by the shelterbelt will result in slightly higher radiation loads immediately adjacent to the shelterbelt than in areas away from the shelterbelt. The area immediately adjacent to the north side of the shelterbelt is shaded most of the day and tends to be cooler and wetter than the south side, which receives direct sunlight essentially all day. As a result, understory species on the north side tend to more shade tolerant species, while species on the south tend to be shade intolerant and more adaptable to drier sites (Hou et al., 2003; Nieto-Cabrera, 1998).

Single row shelterbelts oriented north–south receive morning sun on the east side and afternoon sun on the west side. A study of soybean response to these conditions indicated greater yields on the east side of the shelterbelt (Nieto-Cabrera, 1998). He attributed the greater yield response on the east side to increased radiation availability during the morning hours when temperatures and water stress levels were lower as opposed to the higher radiation loads on the west side during the afternoon hours when temperatures were higher and water stress levels greater. The understory species along the west edge of the shelterbelt were more drought tolerant than ones on the east side (Brandle and Hiller, unpublished data).

The effects of orientation on multiple row shelterbelts are similar to those of single row shelterbelts. In addition, multiple row shelterbelts have the added dimension of the space between rows. Within a shelterbelt, light level between the rows is the primary limiting ecological factor that controls understory development. Canopy structure directly affects light penetration into the canopy, and thus controls the amount of light reaching the soil or litter surface (Larcher, 1995).

Species composition of the understory for both single and multiple row shelterbelts is limited by the availability of seed. Harvey (2000) indicated that native species tend to have an advantage due to a greater availability of seed. Available soil moisture and type of litter are also factors in determining the successful germination and establishment of individual plant species. Sutton (1992) examined woody plant occurrence in hedgerows and fencerows in eastern Nebraska. Native woody species with fleshy fruits (*Morus alba, Celtis occidentalis, Prunus americana*, and *Ribes missouriense*) dominated the reproduction within these linear forests. Only five species with wind dispersed seeds were present. The implication is that bird use of the shelterbelts was the major seed dispersal method. He noted that in the shelterbelts examined, nearly half of the common components of the deciduous forest of eastern Nebraska were missing.

A recent study of 40–year-old, two-row field shelterbelts in Nebraska identified 29 woody species that had been recruited into the shelterbelts (Hiller, 2004). While a taxonomic survey of herbaceous species was not conducted, observations during the sampling for woody species indicated a wider variety of species in the hardwood shelterbelts than in the conifer shelterbelts. For the most part, these differences reflected the density of the canopy and the different light regimes; however, the nature of the litter also may have influenced germination and survival of some species.

An earlier study of these same windbreaks indicated that the type of litter influenced the types of insects that were capable of overwintering in the litter of the shelterbelt (Danielson et al., 2000). Hardwood litter was more conducive to overwintering success than conifer litter. Similarly, the boll weevil (*Anthonomus grandis*) successfully overwintered in hardwood litter but not in conifer litter (Bottrell et al., 1972; Slosser and Boring, 1980).

Shelterbelts contribute to improved soil moisture relationships within the crop field protected by the shelterbelt in two ways: (1) reductions in wind speed reduce evaporation from the soil surface, leaving more water for crop development and (2) low-density field shelterbelts create a broad zone of increased snow deposition across the field on the leeward side of a shelterbelt, leading to an increase in available soil moisture (Kort, 1988; Scholten, 1988). Snow that accumulates within the shelterbelt zone contributes to the growth and development of the shelterbelt.

Dense windbreaks and living snow fences create a deep drift of snow in a narrow band near their leeward sides. They also can be used to create small stock ponds in rangeland areas by depositing snow in low, depressed areas (Jairell and Schmidt, 1990). In both cases, snow management by shelterbelts captures wind blown snow for use within an agroecosystem.

The shelterbelt zone is managed differently from the adjacent cropland. Cropland is cultivated, fertilized, planted, and sprayed with various pesticides annually, but the shelterbelt zone is not cultivated and receives no intentional fertilizer or pesticide inputs. However, limited inputs from adjacent field applications may accumulate within the shelterbelt zone as a result of being deposited via wind erosion, surface water flow or drift. With no cultivation, litter builds up in the shelterbelt zone, increasing soil organic matter and porosity, resulting in changes in soil structure and a shift in populations of various microorganisms (Heal and Dighton, 1986; Juma and McGill, 1986; Bharati et al., 2002). The degree of litter buildup is a function of species composition and environmental conditions, particularly temperature, available moisture, and length of growing season. Forests in the northern latitudes of the USA have slower rates of production of biomass and decomposition of litter compared to those in lower latitudes, and shelterbelts should show similar patterns (Barnes et al., 1998).

If conifers are part of the shelterbelt, their needles will contribute to a deepening litter layer due to their slow decomposition. Litter structure under conifers is more porous than under hardwoods and offers few niches for various types of overwintering insects (Slosser and Boring, 1980). Leaves of most hardwoods break down more rapidly than conifer litter and contribute less to the depth of a litter layer but result in a more rapid build up of soil organic matter (Barnes et al., 1998). Nutrient cycling in these linear forests will start to approximate that of local native forest systems, although the balance of nutrients will depend upon inputs from adjacent cropland and outflows of nutrients due to leaves being blown out of the zone and branches being removed.

As a shelterbelt develops and forms a continuous barrier with more vertical structure, more and different wildlife species will be attracted to the shelterbelt (Best, 1983; Cassel and Wiehe, 1980). Birds that nest, sing, or forage in the shelterbelt will be found more commonly (Johnson and Beck, 1988; Johnson et al., 1994). Given the limited size of most shelterbelts, most bird species that use shelterbelts are edge species; however, the presence of shelterbelts has extended the range of a number of generalist species (Podoll, 1979). A comprehensive review of shelterbelts and wildlife by Johnson and Beck (1988) remains the signature work in this area, and the reader is referred to the original review for more details.

As the barrier and understory communities continue to develop, more non-avian species will begin to use a shelterbelt as a corridor. As shelterbelts age, some predators, both bird and mammal, may increasingly use them for hunting (Gates and Gysel, 1978; Yahner, 1982; Johnson and Beck, 1988). As a narrow forest, large mammalian predators, such as coyote (*Canis latrans*) and red fox (*Vulpes vulpes*), find shelterbelts good hunting grounds; however, rodent and snake predators are not common in these types of habitats. The commonly accepted belief that predators selectively hunt along corridors may only be a concern with larger ground-nesting birds, such as ring necked pheasants (*Phasianus colhicus*) (Shalaway, 1985). A notable exception is the use of field shelterbelts by upland game bird hunters who have found that the number of pheasant or quail taken along shelterbelts is greater than in open fields. A Kansas study indicated significant economic benefits (US$30 million annually) could be attributed to hunters using shelterbelts for upland game bird hunting (Cable and Cook, 1990). The relationship between predator, prey, and shelterbelt habitat needs more study (Johnson and Beck, 1988).

Similarly, the belief that an increase in wildlife abundance will increase the likelihood of damage to adjacent crops needs further examination. Again, the impact appears to apply under certain circumstances. Flocking birds, such as red-wing blackbirds (Agelaius phoeniceus) and European starlings (Sturnus vulgaris), may damage ripe corn (Zea mays) or sunflower (Helianthos spp.) (Bollinger and Caslick, 1985), but in most cases damage can be minimized by timing planting so that crop maturity occurs prior to the appearance of migrating flocks (Johnson and Beck, 1988).

Shelterbelts influence the distribution of both crop pests and their natural enemies (Mineau and McLaughlin, 1996). In addition, more pollinating insects are found in sheltered areas than open areas. For example, honey bee (*Apis mellifera*) flight is inhibited at wind speeds of 6.7–8.9 m/s (Norton, 1988). A number of insects, such as aphids (Homoptera: Aphididae), are carried by wind (Pasek, 1988), and shelterbelts, which reduce wind speed, can reduce the damage associated with aphid-transmitted viruses (Simons, 1957).

Shelterbelts reduce wind erosion and thus reduce damage to the crop. Wind-blown soil can abrade plant tissue, as well as carry inoculum for bacterial and fungal diseases (Pohronezhy et al., 1992). The abrasion causes loss of water control integrity of the epidermal surfaces and potential entry points for pathogens (Hodges and Brandle, 1996). Soil erosion also reduces cropland productivity, and shelterbelts help prevent that reduction. Additionally, shelterbelts, acting as a barrier to flow, can reduce overland flow of water, a cause of rapid, localized erosion. Assuming the soil in the shelterbelt zone is similarly influenced by perennial vegetation as the soil in riparian buffer strips (Bharati et al., 2002), it has a much higher infiltration rate and surface roughness than adjacent cropland, so more water percolates into the soil, benefiting the shelterbelt as well as reducing overland flows.

While these erosion effects are important, the offsite costs of erosion on ecosystems are far greater than the onsite damage (Huszar and Piper, 1986) and include damage to water storage facilities, irrigation systems, road ditches, and other facilities (Ribaudo, 1986). The impacts on air quality and human health (Williams and Young, 1999) are more difficult to quantify but more universal in scope.

Mature Phase

Older shelterbelts continue to provide many of the same ecological functions as younger shelterbelts. As long as they maintain their integrity (forming a uniform and contiguous barrier), they continue to provide the many benefits of shelter described earlier. In fact, the greater height of the older shelterbelt provides an advantage as the extent of the protected zone is enlarged. From a wildlife perspective, mature shelterbelts are more diverse than younger shelterbelts and provide a greater variety of niches for plants, insects, birds, mammals, and other organisms. A shelterbelt enters the mature phase when mortality begins to reduce the integrity of the shelterbelt.

As individual trees within a shelterbelt or a forest approach maturity, their health and vigor begin to decline and eventually the trees die. In a natural forest, dying trees are replaced by trees of the same species or other species, depending upon the age structure of the forest and the species originally present (Barnes et al., 1998). As trees die within a shelterbelt, they might be replaced by other trees, shrubs, or annual and perennial weeds, or the shelterbelt might be cut down and replanted or not. The replacement of trees in a shelterbelt depends upon the management that has been practiced during its lifespan, specifically whether invading trees are removed or not and plans for managing the shelterbelt as the originally planted trees begin to die.

Shelterbelt trees often have shorter life spans than forest grown trees because there are more sources of stress for a tree in an agricultural field than in a natural forest (Fewin and Helwig, 1988; Dix and Leatherman, 1988). Modern agriculture uses many chemical inputs. Fertilizer is one that is commonly used, and trees should benefit from some access to fertilizer applied to adjacent fields. But herbicides also are commonly applied to the same fields, often with multiple sprayings per year, and trees have considerable potential for repeated damage from herbicides. Shelterbelts of any age can be severely damaged or killed by application of herbicides during windy conditions. Additionally, agricultural fields are often cultivated, and the root systems of trees that grow into the field are repeatedly damaged.

As mature shelterbelt trees die, gaps will begin to appear in the shelterbelt. If site conditions are suitable and seed sources are available, these gaps will be filled by new tree or shrub species in a process similar to forest succession if the management of the shelterbelt does not call for the removal of the new trees and shrubs. If conditions are less than ideal, aggressive annual species or perennial grass species, often smooth brome (*Bromus inermis*) in the Midwestern USA, may begin to invade the site, creating greater stress on the trees and increasing the rate of shelterbelt decline.

Nutrients in forest trees are recycled within the forest but that does not often happen with shelterbelt trees. The sequence of regeneration, growth and senescence may or may not occur in a shelterbelt, depending on local conditions and management.

Old shelterbelts have at least three fates. The most common is that they are removed and not replaced. The second fate is removal and replacement. Sometimes a new shelterbelt will be established in the same area immediately after the old one is removed. For producers who are very concerned with maintaining shelter, a new shelterbelt will be established adjacent to an old one some years before the old one is removed (Fewin and Helwig, 1988).

A third fate befalls those shelterbelts that contain an adequate number of trees that became established after the original shelterbelt was planted and are owned by individuals who want to keep the shelterbelt. These shelterbelts are like mixed species, multi-aged forests in which the older trees die out and are rapidly replaced by younger trees that have been waiting in the understory to fill holes in the canopy. These shelterbelts can remain effective for many years but generally require some intervention to control the composition and density of trees that replace the originally planted trees. In England some hedgerows have been dated to be at least 1000 years old (LERC, 2004).

Shelterbelts as a Component of the Landscape

Like all agroforestry practices, shelterbelts represent an intentional addition of woody plants into agricultural landscapes. Shelterbelts are a designed landscape feature in that they are deliberately composed and arranged on the landscape to create specific ecological impacts that we deem valuable. While some of their ecological foundations have been discussed in general (see Olson et al., 2000), shelterbelts have an ecology unique to built ecosystems that we are only now beginning to comprehend in terms of agroecosystem dynamics and sustainability (Paoletti, 2001).

To landscape ecologists, the landscape is composed of three elements: a matrix, which is the predominant plant and animal community; patches, which are plant and animal community areas surrounded by areas with different community structure; and corridors, which are narrow plant and animal communities that connect patches (Figure 3.1) (Forman, 1995). Shelterbelts are corridors – introduced buffers – placed into a matrix, which is usually an agroecosystem characterized by intense human intervention. The ecological interactions between shelterbelts, as corridors, and the other two landscape elements defines the targeted or intended services being sought from shelterbelts, as well as the many unintended impacts that may or may not be considered beneficial (Schoeneberger et al., 1995; Schmucki et al., 2002).

Although shelterbelts generally comprise a very small portion of the landscape, the impact of their structural diversity in the highly simplified and massive agricultural matrices is many times greater than the small portion of land they occupy (Guertin et al., 1997). Placement of shelterbelts and other introduced corridors, such as riparian buffer strips, into the agricultural matrix alters numerous ecological functions that translate into impacts at the site level, aggregating upwards to the farmscape, and beyond (Figure 3.2a–b). Managing these impacts to our benefit requires an understanding of how the five main corridor functions – habitat, conduit, filter/barrier, sink, and source – change over a shelterbelt's life (Tables 3.1 and 3.2) (Hess and Fischer, 2001). Operating simultaneously, these five functions vary seasonally and with the weather, and change dramatically over a shelterbelt's life span.

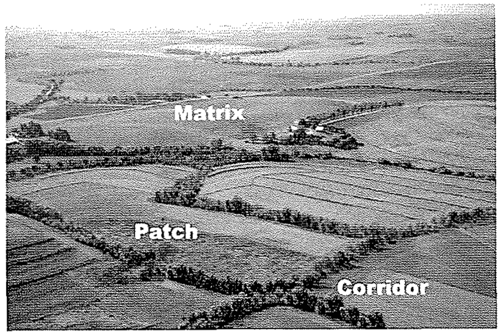


Figure 3.1 Shelterbelts, as a designed corridor within the agricultural landscape

While this approach oversimplifies the many and highly complex interactions that take place, it does provide a scientific framework for guiding shelterbelt design and management over time. We can create or manage the ecological functions of shelterbelts by making decisions on shelterbelt design, location, and orientation at the time of establishment and/or by deliberately manipulating the structure throughout its life span. Manipulating the width, connectivity, architecture, length, composition, and the edge-to-interior ratio changes the biological and physical characteristics of a shelterbelt.

Because the dominant use of shelterbelts is as a filter/barrier for microclimate modification, the first scale of consideration is at the practice (field) or individual corridor level. The architecture or structure of a corridor is the primary concern. Structure is defined as the amount and arrangement of the solid and open portions of a shelterbelt and for microclimate modification is often expressed in terms of shelterbelt density (percentage of the solid portion) or porosity (percentage of the open portion). The relationship between structure and function is the subject of current research, and a detailed discussion can be found in Zhou et al. (2005) and Brandle et al. (2004). In general, dense shelterbelts create large wind speed reductions over short distances and are used to protect buildings, livestock, and roads, while more porous shelterbelts create moderate wind speed reductions but over greater distances and are used to protect fields and crops.

Maximizing the filter/barrier function of shelterbelts, therefore, entails design decisions at establishment regarding species selection and planting arrangement (length, width, and orientation) and management practices as needed throughout the life span to maintain the appropriate density. Examples of other important corridor functions and their implications for management are briefly listed in Table 2.2 and were discussed in the section on the three phases of a shelterbelt's life. It is critical to note that many of the functions created by shelterbelts operate at scales larger than an individual property or practice and must be taken into account if the overall impacts from these plantings are to have a net benefit to the landowner or larger stakeholder group. For example, the conduit function of corridors for large wildlife occurs at landscape scales (See Box 3.1).

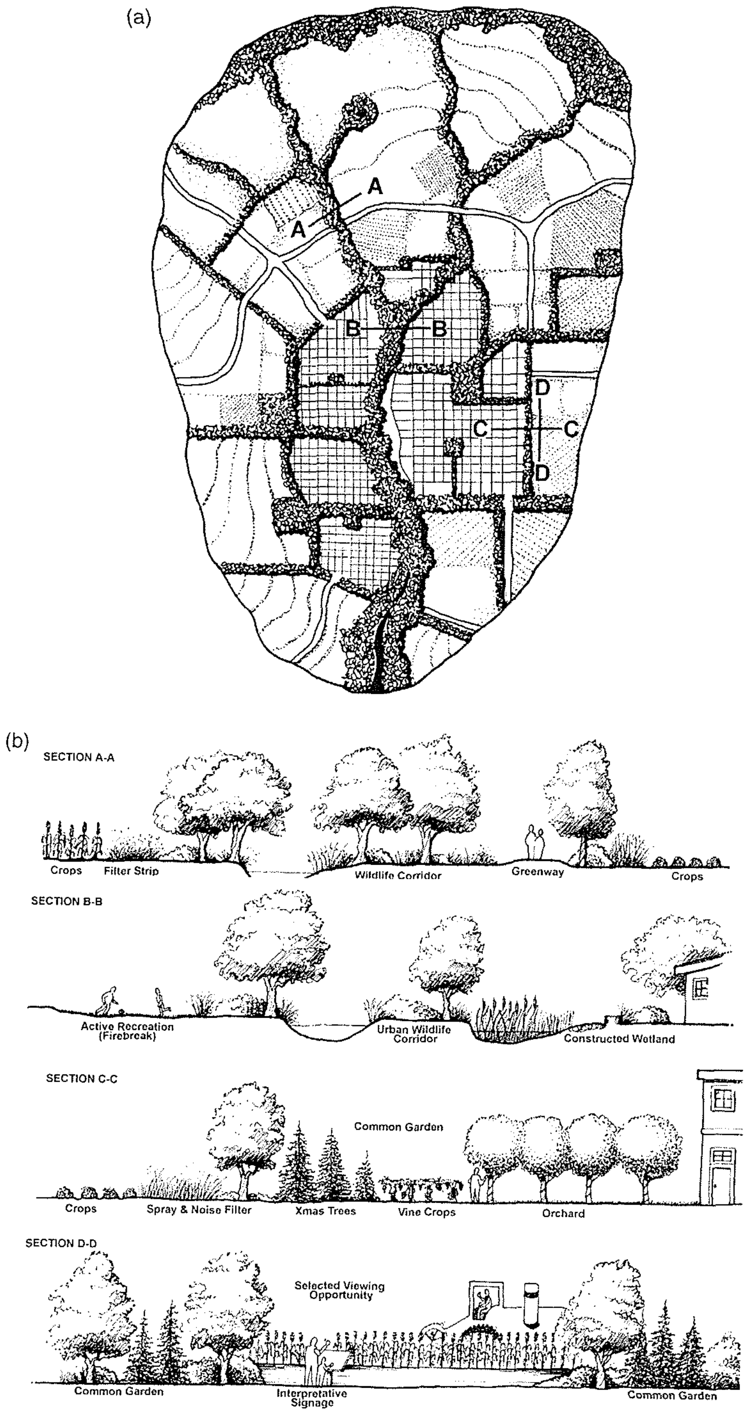
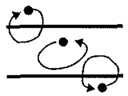
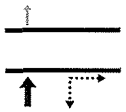
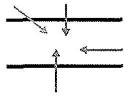
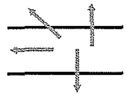


Figure 3.2 a, b Overview of ecological impacts throughout a farmscape created by shelterbelts and other agroforestry plantings. (Modified from Forman and Baudry, 1984)

Table 3.1 General description of main corridor functions. (Adapted from Schoeneberger et al., 2001.)

Corridor function	Description	Application to shelterbelts
 Habitat	Provides resources (e.g., food, shelter, reproductive cover) to support an organism's needs	Provide critical wildlife habitat oasis for numerous wildlife species within the dominant agricultural ecosystem.
 Conduit	Conveys energy, water, nutrient, seeds, organisms, and other elements within the linear elements.	Travel corridors that enable movement of wildlife across agricultural landscape – either between critical patches or as an oasis along migratory pathways.
 Filter/Barrier	Intercepts wind, wind-blown particles, surface and subsurface water, water-carried materials (e.g. nutrients, pesticides, sediments), genes, and animals.	The dominant function managed for in shelterbelts. Shelterbelts are constructed to serve as barriers predominantly to wind and wind-carried particles. They filter dust, agrochemical drift, odors, and other particulates.
 Sink	Receives and retains objects and substances that originate in the adjacent matrix of land.	Windbreaks tend to serve as sinks for many agricultural products and by-products, including eroded and wind-blown top soil, fertilizers, pesticides and other chemicals, seeds, and animals.
 Source	Releases objects and substances into the adjacent matrix of land.	Windbreaks may serve as a source of weed seed and other pests, such as deer and other animals that damage crops. They may also serve as a source of beneficial organisms, both insects and birds that can serve as natural enemies to crop pests.

Shelterbelts: A Component in Sustainable Land-use Management

Shelterbelts in North America came into early prominence primarily as a filter/barrier tool to combat the Dust Bowl of the 1930s. Today, society's demand for more sustainable agricultural production systems and landscapes is placing new requirements on shelterbelts. No longer should shelterbelts be established for one benefit. They must be designed to perform multiple corridor functions and provide several services (Lassoie and Buck, 2000).

Shelterbelts, along with other agroforestry practices, are being promoted globally as a means to create critical environmental and economic linkages across the agricultural, urban, and forest continuum (Ruark et al., 2003). For the strategic

Table 3.2 Examples of corridor functions of shelterbelt and their management implications

Corridor Function	Examples	Management implications
Habitat	Habitat for bird and bat species that feed on crop pests (Johnson and Beck, 1988)	Increase corridor width to minimize nest parasitism by cowbirds
		Leave dead trees standing for snags habitat
	General habitat for parasitoids and other beneficial insects (Marino and Landis, 1996)	Establishment of structurally diverse shelterbelts. Provide specific plant species necessary for maintaining beneficial insects
Conduit	Movement corridors for desirable species at risk (Anderson, 1997)	Use the shelterbelt to connect other habitat patches Use similar species and structure found in the habitat patches
	Movement corridors for undesirable species	Avoid connecting patches that are colonized by undesirable species
	Integrate shelterbelt into regional pedestrian trail system where appropriate	Increase corridor width to accommodate the range of desired functions
Filter/Barrierv	Concentration of wind dispersed weed seeds on windward side	Minimize area required for active weed treatment and management
	Visual screen separating land uses or undesirable views	Use species that provide screening benefits year around
	Interception and concentration of pollutant laden runoff	Provide understory vegetation to trap and retain pollutants
	Provide energy savings for human-based structures (DeWalle and Heisler, 1988)	Establish appropriate species to provide solar and wind protection
	Trap airborne chemical drift and odors from affecting adjacent areas	Use species on outside edge that are tolerant of chemical drift
		Silvicultural treatment to maintain a dense barrier
	Reduction of noise from agricultural fields and roads	Establish shelterbelt close to noise source
		Use dense, branching species, particularly evergreens
Sink	Weed proliferation during establishment phase	Use appropriate mulches or cultivation to control weeds
	Storage of carbon in woody biomass	Provide long term management of vegetation to sequester carbon
	Capture and deposit snow to protect structures, roads, and livestock	Silvicultural treatment to maintain 60–80% porosity to accumulate snow
Source	Insect pests of crops: boll weevils (*Anthonomus gradis*) and alfalfa weevils (*Hypera postica*)	Silvicultural treatment of shelterbelt to destroy pest habitat
		Use of pesticides to control pests
	Animal pests of crops: deer, elk, rabbits, and rodents	Minimize proximity to other travel corridors
		Alter interior structure to create less favorable habitat
	Natural enemies of crop pests (Altieri and Letourneau, 1982)	Manipulation of edge-to-interior ratio in shelterbelt "forest"
		Manage species composition and density
	Provide alternative economic products (i.e. medicinal herbs and woody florals)	Integrate marketable species into planting design

Box 3.1 Louisiana Black Bear Use of Corridors. (From Anderson, 1997; Johnson et al., 2000.)

The Louisiana black bear *(Ursus americanus luteolus)* was once abundant in east Texas, southern Mississippi and all of Louisiana. Habitat loss and fragmentation have diminished the range of the black bear by 90–95%. In January 1992, the US Fish and Wildlife Service designated the Louisiana black bear as threatened under authority of the Endangered Species Act.

In 1994, wildlife biologists at the University of Tennessee initiated a study of corridor use and feeding ecology of black bears in the Tensas River Basin in northern Louisiana. The 350 km^2 privately owned study area contained four major isolated woodland patches, some linked by wooded corridors. The patches were surrounded by agricultural fields of corn, soybeans, cotton, wheat, and other small grains. Corridors in the study area ranged from 50 m to 73 m in width. The height and density of vegetation in most corridors was sufficient to conceal bear movements.

Radio collars were placed on 19 Louisiana black bears, and their movement was tracked over 18 months. Analysis of telemetry data indicated that bears preferred corridors to agricultural fields when outside of a forest track. Fifty-two percent of the male bear patch-to-patch movement and 100% of the female bear movement was between patches connected by corridors. Adult male bears used the corridors most intensively in June and July, the breeding season. Sub-adult bears used the corridors for dispersal from their natal home range.

This study suggests that wooded corridors between forested tracts may be vital to the survival for the Louisiana black bear in highly fragmented landscapes. Long-term management should include maintenance, enhancement and implementation of wooded corridors that link forested patches. Shelterbelts and other woody corridors provide a means to maintain agricultural production while providing other key environmental services.

incorporation of shelterbelts and similar plantings to occur, two different scales of considerations and planning must be melded: (1) the sustainable agriculture level, where whole-farm resource use is balanced with whole-farm productivity and (2) the sustainable landscape level, where agroecosystems, along with public and urban lands, are components of a larger watershed (Barrett et al., 1999).

Because 50% of the USA (approximately 360 million hectares) is in agricultural production, the importance of agricultural lands in determining the health of land in the USA is evident (USDA, 1996). Strategies at this scale entail a more holistic approach and require a broader consideration of concerns, land uses, and stakeholders within the larger watershed encompassing agricultural activities. Ultimately, shelterbelts will need to be integrated with other corridor types for societies to achieve the range of goals and services desired from their lands (Figure 3.3).

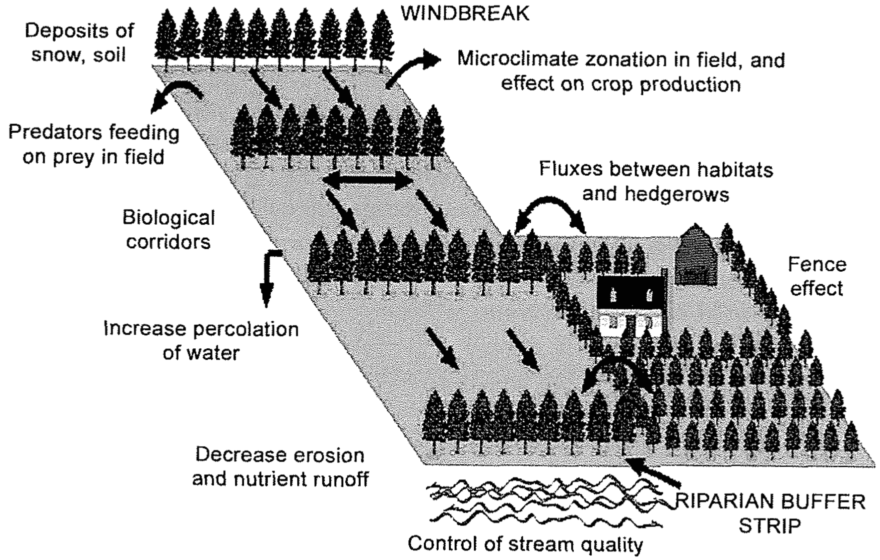


Figure 3.3 Integration of shelterbelts with other corridor systems to achieve landowner and community-based goals

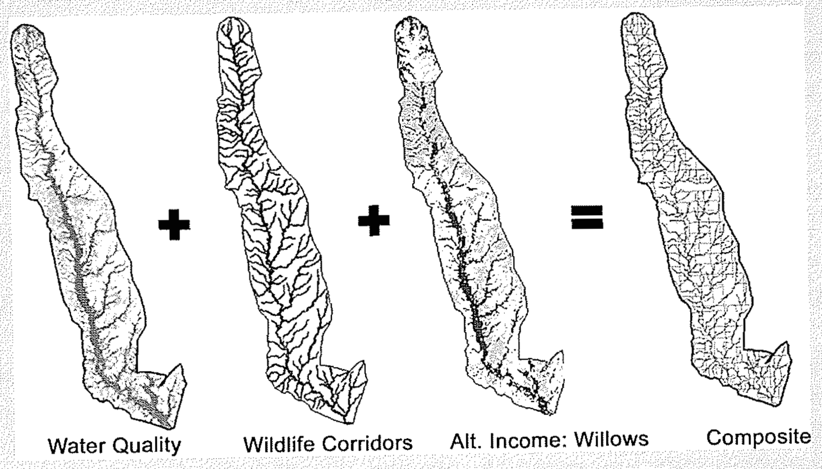
In this conceptual example, shelterbelts and other corridors and patches are purposely designed and linked together in a manner that promotes the desired landowner and community-driven goals. In Section A-A, the corridor is designed to treat runoff by filtering runoff through a dense vegetative buffer that also provides habitat and a conduit for wildlife. This corridor also allows for passive recreation through a greenway trail, allowing urban residents to experience agricultural environments. In contrast, Section B-B illustrates a corridor in a more urbanized section of the watershed. Because stormwater flow is more concentrated, a constructed wetland is designed in the shelterbelt system to treat the stormwater before it flows into a stream. A more active recreation area is included in the corridor, which also serves as a firebreak to protect homes.

A shelterbelt between an agricultural field and residential area is presented in Section C-C. In addition to improving the mircoclimate for the adjacent crop field, the area also serves as a common garden for local residents and is protected from noise and spray by a vegetative buffer. Section D-D illustrates how this same shelterbelt can provide views and awareness of conservation measures being applied to protect natural resources.

This example demonstrates how the objective of the shelterbelt or corridor will play a key role in determining the location and design parameters for a particular segment of the corridor system. The next step is then determining strategic arrangements within the context of the working landscape. Geographic Information Systems (GIS) provide an effective and efficient means to analyze landscape characteristics (i.e. slope, soil type, land cover) in the identification of suitable shelterbelt and other corridor locations that can address the desired objectives (See Box 3.2). GIS-based assessments developed at a state or multi-county level can be valuable in preparing technology transfer programs and for prioritizing resources and projects, while county-level assessments can be useful in the site specific design process (Bentrup and Kellerman, 2004).

Box 3.2 Soldier Creek Watershed: Achieving Multiple Objectives with GIS. (From Bentrup and Leininger, 2002; Bentrup and Kellerman, 2004.)

The Soldier Creek watershed, a 500 km^2 region in northeast Kansas, is typical of many watersheds in the western Corn Belt ecoregion. Once covered with tallgrass prairie, over 90% of the ecoregion is now used extensively for cropland and pasture. Landowners and community leaders in the Soldier Creek area are interested in using wooded buffers to help mitigate water quality problems while providing benefits to wildlife. GIS was used to identify the best locations for implementing buffers to treat runoff and provide wildlife habitat and movement corridors. Because these proposed plantings would take land out of traditional agricultural production, landowners were concerned about losing income. Another GIS assessment was developed to determine where non-timber specialty products could be grown to diversify landowners' enterprises and replace the potential loss in income. In the illustration below, suitable locations for growing willows for the decorative floral industry were determined. By combining the three individual GIS assessments, sites were identified where buffers could achieve water quality, wildlife, and economic goals, allowing planners to prioritize efforts on private lands.



More extensive discussion on this topic is beyond this review; however, we can point out other publications and efforts that are addressing the need for tools and approaches to help guide the incorporation of agroforestry plantings, like shelterbelts, into the larger spatial context. One such effort in the USA is *Conservation Corridor Planning at the Landscape Level – Managing for Wildlife Habitat Manual*

(Johnson et al., 2000), developed in response to the nationwide promotion of buffers through the National Conservation Buffers Initiative. Directed at managed corridors in agriculturally dominated landscapes, this handbook serves as a source for ideas and planning principles for wildlife corridor planning at site and landscape scales.

Because every application of shelterbelts and other plantings is based upon a unique mix of biophysical, social, and economic considerations, a suite of flexible tools is needed to accommodate the range of considerations and each individual's or group's unique decision-making process (Bentrup et al., 2003; Ellis et al., 2004) (Box 3.3). The Comprehensive Conservation Buffer Planning Methodology being developed at the USDA National Agroforestry Center (www.unl.edu/nac) facilitates this process and dialog among stakeholders, while providing information on the dynamic interactions and potential tradeoffs of tree-based buffers, such as shelterbelts. This loosely coupled suite of tools is being developed to address multiple issues and ranges from the *Conservation Planning Atlas* and GIS-guided suitability assessments addressing water quality, wildlife habitat, and income diversification to *BUFFER$* (a conservation buffers economic analysis tool) and a computer-based visual simulation tool (*www.unl.edu/nac/conservation/index.html*).

Central to the planning effort is the simply illustrated and written *Conservation Buffers: Planning and Design Principles* manual that facilitates landowner and stakeholder discussion regarding the ecological principles that can be applied in the design and management of agroforestry plantings (see Box 3.4).

Shelterbelts and other agroforestry plantings are not a panacea for addressing sustainability issues, but with appropriate tools that integrate and balance site,

Box 3.3 Shelterbelt Planning and Design Tools. (From Bentrup et al., 2005.)

This list provides a sample of tools and publications available for planning and designing multifunctional shelterbelts at site and landscape scales to achieve landowner and community-based goals.

Conservation Planning Atlas: An internet-based atlas of over 100 national and regional-scale resource maps. http://www.unl.edu/nac/conservation/

BUFFER$: An economic analysis spreadsheet tool for evaluating the installation or removal of buffers in a crop field. http://www.unl.edu/nac/conservation/

WBECON: A tool that calculates the economics of windbreaks by taking into account various factors, such as windbreak species, windbreak design, soil and climate factors, crop rotation, windbreak costs, crop costs, and crop prices. http://waterhome.brc.tamus.edu/NRCSdata/models/Forests and Windbreaks/WB/

Visual Simulation Kit: A two CD collection containing a photo-editing software program and a how to guide for creating visual simulations of proposed conservation design and management scenarios. http://www.unl.edu/nac/simulation/

Habitat Suitability Index Model: Wildlife Species Richness in Shelterbelts: A simple model for evaluating species richness based on structural parameters of a shelterbelt.
http://www.nwrc.usgs.gov/wdb/pub/hsi/hsi-128.pdf

Conservation Corridor Planning at the Landscape Level – Managing for Wildlife Habitat Manual: *http://www.wsi.nrcs.usda.gov/products/tools.html*

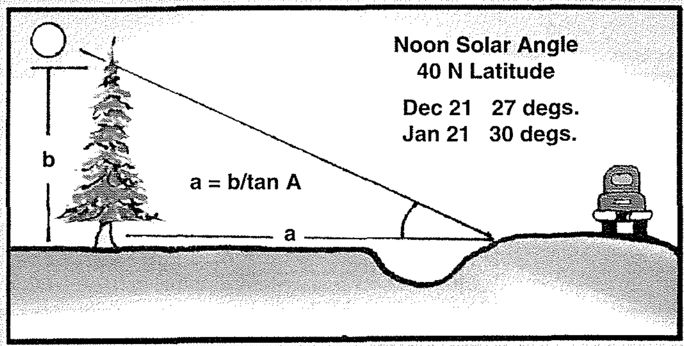
PLANTS: A national plant database maintained by the USDA. http://plants.usda.gov/

USDA National Agroforestry Center: A multi-agency organization promoting agroforestry in rural and urban environments. http://www.unl.edu/nac/

PFRA Shelterbelt Centre: A Canadian organization that promotes the integration of trees in agroecosystems. http://www.agr.gc.ca/pfra/shelterbelt.htm

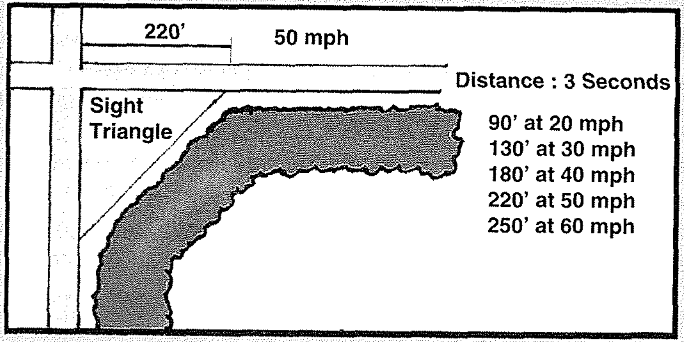
Box 3.4 Conservation Buffers: Planning and Design Principles. (From Bentrup et al., 2005.)

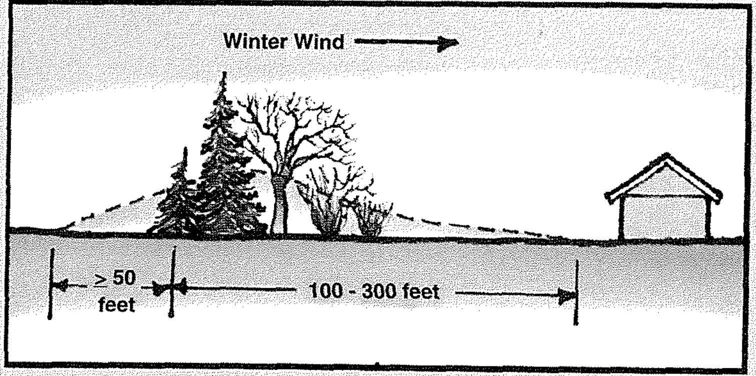
Over 80 illustrated planning and design concepts for shelterbelts and other corridors are presented in this guide gleaned from a diffuse body of research and literature. Information was synthesized from landscape ecology, conservation biology, agricultural engineering, agronomy, economics, social sciences, and other disciplines. The principles were organized into seven resource categories: water quality, species and habitats, productive soils, economic opportunities, protection and safety, aesthetics and visual quality, and outdoor recreation. By providing an easy way to incorporate current research into the design of multifunctional buffers at landscape and site-scales, this guide should facilitate the considerations of landowners and/or community issues in the buffer planning process. Below is an example page from this guide.

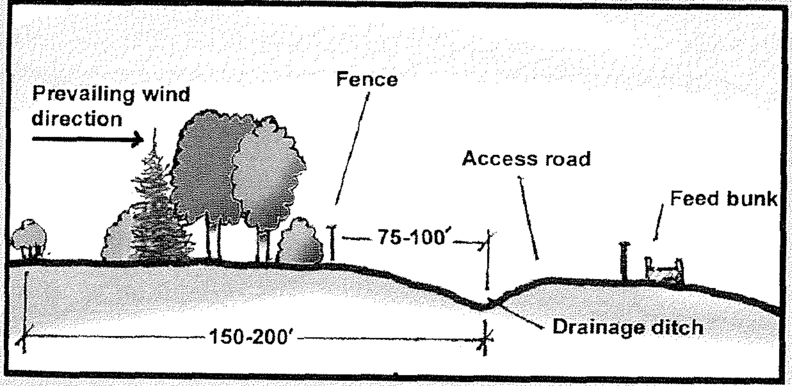


(continued)

Box 3.4 (continued)







landscape, and even regional-level concerns, we can begin to design strategic systems that create more sustainable landscapes.

Summary

Shelterbelts are linear forests established on the landscape to address various conservation goals. These designed corridors provide protection from wind to crops and livestock, store carbon, and offer habitat to numerous insects, birds, and small mammal. As we better understand their function, we will be able to utilize them more efficiently to create more stable landscapes. Shelterbelts are not panaceas, but as our understanding of their function at the landscape level increases, they will become a significant part of the tools used to create healthier agroecosystems in North America and other parts of the world.

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Chapter 4
Forage Production Under and Adjacent to *Robinia pseudoacacia* in Central Appalachia, West Virginia

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Introduction

Species-diverse production systems, such as agroforestry, provide opportunities to increase the value of total production through marketing of multiple products from a given unit of land. Designing successful systems requires an understanding of how species compete for resources and grow in proximity to other species with distinctly different growth habits and resource demands (Sanchez, 1995; Ong and Leakey, 1999). Systems successful in a particular soil-climate environment may not be productive or sustainable in others (Ong et al. 1991). Soil fertility, texture, and depth along with temperature, timing and amount of precipitation, solar radiation levels, and topography provide a wide array of site conditions that generates a virtually continuous array of growing conditions.

The Appalachian Region of the eastern United States is characterized by steep, complex topography and a humid, temperate climate. Agricultural production is mainly from small farms averaging 60 ha with 40% of that land area occupied by woodlands (USDA, 1999). Since the terrain is steep and fiscal resources limited in many cases, highly mechanized and chemical-dependent crop production is limited. The dominant form of agriculture, on an area basis, is the production of perennial forage grazed by beef cattle. This form of agriculture does not generate enough income to support a family on an average farm, thus off-farm jobs are the norm.

Agricultural systems that offer some prospect of increasing income and providing environmental services are desirable. The Appalachian Region is economically depressed relative to most of the United States. The headwaters of most major river systems in the eastern United States are located in the region. Since these river systems provide water for many major population areas in the eastern United States, it is important that increased agricultural production is not achieved at the expense of water quality.

One approach to improving small farm productivity is to implement silvopasture systems that provide tree- and forage-based income-generating opportunities.

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach*.

The type of tree (or trees) chosen will be a function of site characteristics as well as the management priorities of the landowner. One species with potential for creating successful silvopastures on many sites is black locust (*Robinia pseudoacacia* L.) (Powers et al. 1996).

Black locust is a multipurpose tree native to Appalachia although it was introduced and grows throughout much of Eastern Europe and temperate Asia (Keresztesi, 1988). Leaves begin to appear in late spring and senesce early in autumn. This minimizes the time during the growing season when forages are shaded relative to other deciduous tree canopies. However, microclimate is altered substantially while black locust is in leaf (Feldhake, 2001). The tree produces a dense, rot-resistant wood that is excellent for fence posts and firewood (Youker, 1965; Barrett and Hanover, 1991). It is a legume that adds nitrogen to the soil and has aromatic flowers from which bees produce highly valued honey.

It was noted decades ago that pasture productivity was enhanced in proximity to isolated black locust and black walnut (*Juglans nigra* L.) trees in Ohio (Smith, 1942). However, in Tennessee under trees planted on 9 m centers, and with recent near-closed canopies, productivity increased under black walnut but decreased under black locust (Neel, 1939). In central Illinois, grasses established and persisted under black locust on sand dune soils in places where they would otherwise have not (Gustafson, 1935). The biggest limitation to black locust in its native range is that it is susceptible to insect pest damage, especially the locust borer (*Megacyllene robiniae* Forester), which can cause serious damage in large monoculture stands of this tree (Hoffard, 1992). However, some genetic material seems to have resistance to borer (Hall, 1937).

Since black locust is a legume, there has been considerable interest in the amount of nitrogen fixed by this species. Mulched juvenile material (2.5% N) released 86% of its N in the first 6 weeks when buried in mesh bags, which approached the amount contributed by alfalfa (*Medicago sativa* L.) (Bross et al. 1995). The remaining material was only 4.6% of the original dry weight. Senesced leaf litter, which contained 2.2% N retained 81% of its N after 863 days buried in mesh bags (White et al. 1988). This suggests senesced material provides a long-term N source for subsequent vegetation. Stands aged 4, 17, and 38 years accumulated 48, 75, and 33 kg N ha^{-1}, respectively suggesting nearly mature but vigorously growing trees are the most efficient at fixing N (Boring and Swank, 1984). A significant flux of N into the soil is also provided through root exudation (Uselman et al. 1999). Competition for water can outweigh the benefits of the N contribution. In an alley-cropping system, barley (*Hordeum vulgare* L.) along black locust row edges was suppressed relative to plants growing in the center of the alley but when trees were cut down the reverse occurred the following year (Ntayombya and Gordon, 1995).

The forage component of silvopasture systems varies by region, species, and tree association. Large-scale screenings under shade cloth provide an estimate of response to variation in the solar radiation resource component (Watson et al. 1984; Lin et al. 1999). However, field responses may vary. Orchardgrass (*Dactylis glomerata* L.) yield in Arkansas improved in proximity to pine (*Pinus* sp.) but tall fescue (*Festuca arundinacea* Schreb.) yielded less (Burner, 2003). The response of forages to tree overstory can vary by tree species and geographic location (Ratliff et al. 1991). In the southern and northwestern United States utilizing pine understories for grazing can add value to the system through animal production and increase tree growth by limiting understory vegetation and recycling nutrients, thus some reduction in forage yield relative to open sites may be acceptable (Jaindl and Sharrow, 1988; Clason, 1999). There are many potential silvopasture systems, varying by region and management objectives, with research needed to assist landowners in implementing profitable, sustainable production.

Our objective was to determine how forage yield from a typical, moderately well-managed site was affected under and in proximity to black locust in a humid temperate hill pasture of Appalachia.

Materials and Methods

The site on which this research was done is a near-level bench on the northeast face of a steep knoll in Raleigh County of southern West Virginia, USA (38°10′ N, 81°00′ W). The elevation is 920 m and the 1 m deep soil is a mixture of Gilpin and Berks-Pineville complex (fine-loamy, mixed, mesic, Typic Hapladults). Black locust saplings were planted in 1992 in 12 m-spaced rows perpendicular to the primary drainage. Trees were 1.5 m apart within each row. The first 3 years, a 1 m strip along the tree rows was sprayed with Roundup (glyphosate) to suppress competing vegetation. At the time of this study the trees were 8 m tall and provided a foliage canopy width along the rows of 5 m. Branches were pruned from the trunk up to 2 m. Forage between rows of trees was dominated by tall fescue. In the spring of 2000, the site was fertilized with 45, 147, and 168 kg ha^{-1} of N, P, and K, respectively and over-seeded with 8 kg ha^{-1} ladino white clover (*Trifolium repens* L.).

Three replications of 12 plot yield strips were harvested in 2001, 2002, and 2003 (during growing years 9, 10, and 11, respectively). Two sets of six 0.7 × 4 m strips were spaced between tree rows with the long axis parallel to tree rows (Figure 4.1). Three- and six-week clipping frequencies were imposed on strip sets 1 and 2, respectively. Species composition was estimated in spring, mid-summer, and fall of each year using a point intercept method (Warren-Wilson, 1959), and measuring 50 points from each harvest strip.

Soil moisture for the top 15 cm was measured for each plot strip at near-weekly intervals, the first 2 years, using a Trime-FM TDR (MESA Systems, Medfield, MA) soil moisture meter. Soil temperature at 6.5 cm was also measured weekly the first 2 years for each plot with a stainless steel, thermister-tipped probe (Yellow Spring Instruments, Yellow Spring, OH). Measurements were made from late May through late October. Photosynthetically active radiation (PAR) was measured periodically for each plot location relative to tree row during the growing season using a system of 16 Li-Cor Li-191-SB line quantum sensors (Li-Cor, Lincoln, NE) and collecting data into 21X data loggers (Campbell Scientific, Logan, UT) with measurements made every 10 s and averaged into 1 h values.

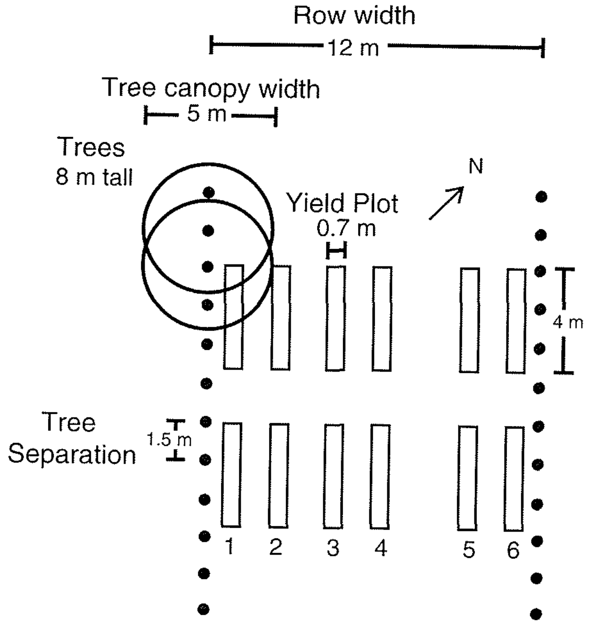

Figure 4.1 Schematic showing plot sites in relation to tree rows. The numbers under the bottom row of plots indicate site position label

Year and harvest frequency and site yield, soil moisture, and soil temperature were tested for differences at the spatially variable PAR levels using one-way analysis of variance since only main effects were tested and not interactions. Differences between individual sites were tested using Tukey's separation of means.

Results

Average daily maximum monthly temperatures did not exceed 26 °C for any of the 3 years (Table 4.1) at this site. Monthly PAR averaged about half of maximum possible because of cloudiness. Precipitation was ample and well distributed all 3 years except for brief periods of drought that occurred in September–October 2001 and again in August 2002. Soil moisture remained at desirable levels throughout most of the growing season but declined as expected during late-season droughts in 2001 and 2002 (Figure 4.2). Average soil temperatures remained around 22 °C during most of the growing season (Figure 4.3).

Relative levels of PAR under trees varied throughout the growing season since black locust has an indeterminate growth pattern. At this site leaves begin appearing in early to mid-May and stems and leaves expand as long as growing conditions allow. Site 1, which is under the northeast side of the tree canopy, on 15 May received about 80% of the total daily PAR received by site 4, the mid-alley position. The percentage received by site 1 decreased as the canopy developed until summer

Table 4.1 Growing season average monthly maximum and minimum daily temperatures, average daily PAR, PAR relative to maximum possible and monthly total precipitation

	Month	Average 24 h Max Temp. (°C)	Average 24 h Min Temp. (°C)	Average PAR (mol^{d-1})	Average Relative PAR	Total Precip. (cm)
2001	March	5.7	–2.5	19.9	0.56	6.8
	April	17.7	6.8	29.8	0.62	4.3
	May	20.1	10.4	29.5	0.52	16.3
	June	23.7	14.2	33.1	0.55	9.3
	July	23.5	15.2	28.4	0.48	26.6
	Aug.	25.5	16.5	27.3	0.53	9.0
	Sept.	20.1	10.3	24.6	0.61	3.3
	Oct.	16.3	5.7	21.3	0.75	2.3
2002	March	10.3	–0.7	17.7	0.49	14.1
	April	16.9	5.7	26.4	0.55	10.4
	May	19.5	8.4	28.0	0.49	10.9
	June	24.6	15.1	30.5	0.51	8.4
	July	25.5	17.1	29.2	0.51	18.1
	Aug.	25.5	16.6	32.3	0.63	2.4
	Sept.	23.9	13.8	24.9	0.61	11.8
	Oct,	14.1	7.3	12.2	0.43	13.3
2003	March	11.8	0.7	20.2	0.56	3.4
	April	16.3	5.8	25.3	0.52	15.0
	May	17.7	9.5	23.1	0.41	15.8
	June	21.5	12.7	31.3	0.52	12.5
	July	24.3	15.6	31.5	0.54	13.5
	Aug.	25.4	16.5	28.1	0.54	9.8
	Sept.	20.4	11.3	24.4	0.61	16.5
	Oct.	15.4	5.5	18.2	0.64	5.9

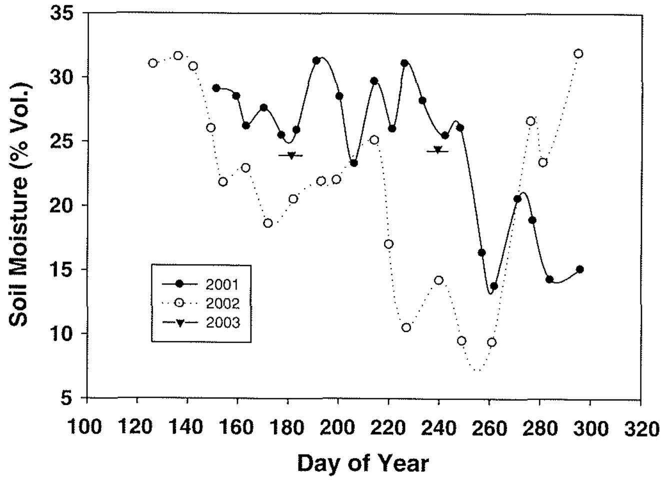

Figure 4.2 Average location percent soil moisture for the top 15 cm by volume for 2001, 2002, and 2003 in response to weather conditions during the growing season. There are only two points for 2003 since it was a very rainy summer and soil moisture remained high

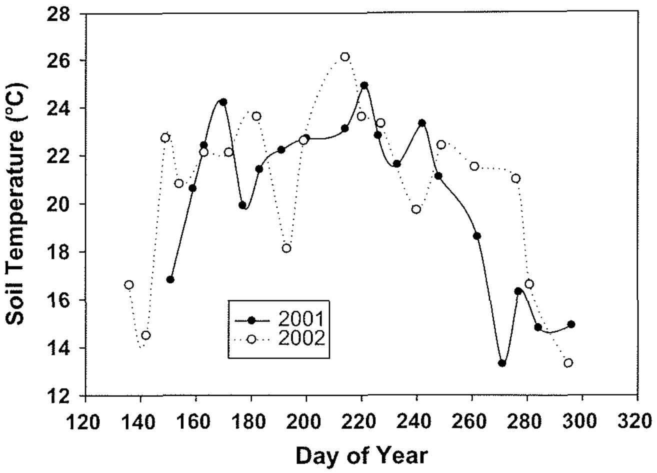

Figure 4.3 Average location soil temperature for the growing seasons of 2001 and 2002 taken at 6.5 cm during early afternoon on mostly sunny days

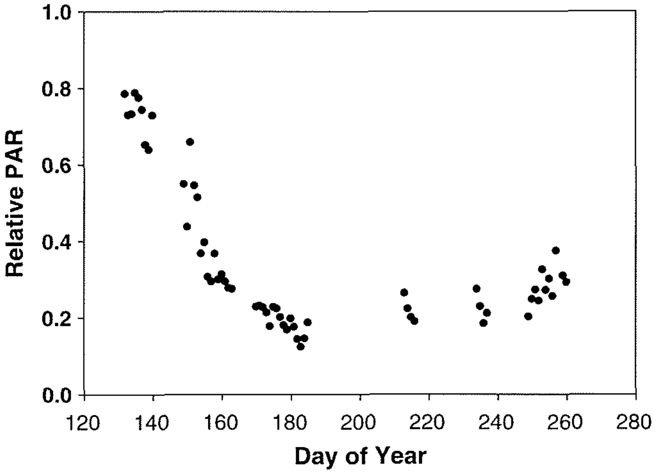

Figure 4.4 PAR of harvest strip site 1 under the trees relative to site 4 in the alley center

solstice (21 June) when it was only about 20% of the amount received by site 4 (Figure 4.4). Predation by insect pests typically degrades the tree canopy allowing increased light penetration during late summer. Leaves began senescing and falling in late September preventing late growing season PAR measurement since leaves on sensors compromised data collection.

For comparison purposes PAR at site 4 was assigned a relative value of one even though early and late in the day, when direct beam PAR was very low, that site did receive brief shade. Level, treeless sites in Appalachia are atypical so this is a reasonable approximation, within a few percent, for maximum possible daily PAR for similar locations. Relative to site 4, both sites 1 and 6 received 20% of possible PAR, site 2 received 40% of possible PAR, and sites 3 and 5 received 80% of possible PAR (Table 4.2). There were small but significant differences in both soil moisture and soil temperature across site positions. Seasonal averages of both were 2% and 2 °C higher respectively in the center of the alley compared to under tree canopies (Table 4.2). Differences were greater for hot periods with reduced soil moisture but less for cloudy wet periods (data not shown).

There were significant differences in yield between years, between harvest dates within years and between differences in total yield between a 6-week harvest and two 3-week harvests totaled ($P<.05$). Total seasonal harvest for 2001, 2002, and 2003, respectively for all site positions averaged was 4040, 3670, and 5120 kg ha^{-1}. Average yield for the four 6-week growth increments was 1700, 1020, 950, and 620 kg ha^{-1}. The average yield for the sum of two 3-week harvests and the corresponding 6-week harvest was 960 and 1180 kg ha^{-1}. The difference in yield between the combined 3-week and corresponding 6-week periods was primarily due to values from the first 6-week period in 2001 and 2003 and the later harvest periods in 2002 (Figures 4.5a–f).

Average yield by site within the alleys was not significantly different in 2001, 2003, or for all 3 years combined (Table 4.3). However, during the dry 2002 growing season, there was a significant difference between the highest PAR site (4) and the two lowest PAR sites (1 and 6). Site 4 yield was about 25% higher than sites 1 and 6. The difference between sites was not due to drought, however, since there was no significant difference between sites for the harvest following the drought even though overall yield was reduced (Figures 4.5c–d).

On an area basis, species composition of forage plots varied in relation to proximity to tree rows. Tall fescue was the single largest component for all plots (Figure 4.6a). However, tall fescue varied significantly between sites comprising slightly less than 50% of sward composition in the alley centers but about 60% under tree canopies. Orchardgrass was nearly constant across all plots at about 10% (Figure 4.6b). Clover content of plots varied significantly with location relative to tree row, with less than 5% clover in swards under trees and up to 25% in alley centers (Figure 4.6c). Other grasses and weeds, in addition to bare soil patches, were slightly more prevalent under trees compared to alley centers (Figures 4.6d,e).

Table 4.2 Harvest site PAR relative to alley center, average seasonal soil moisture, and average seasonal soil temperature. Values in the vertical column followed by the same letter are not statistically different at $P<.05$

		Soil moisture (%)		Soil temperature (°C)	
Site	PAR (%)	2001	2002	2001	2002
1	0.2	23.3 c	21.0 c	19.2 e	19.5 c
2	0.4	25.9 a	23.2 a	20.3 d	20.6 b
3	0.8	25.7 a,b	23.1 a	21.5 b	21.8 a
4	1.0	24.9 b	22.5 b	21.7 a	22.0 a
5	0.8	23.3 c	20.8 c,d	20.6 c	20.7 b
6	0.2	22.9 c	20.3 d	18.8 f	19.0 d

Within vertical columns means with the same letter are not significantly different at the 0.05% level (Tukey's HSD test)

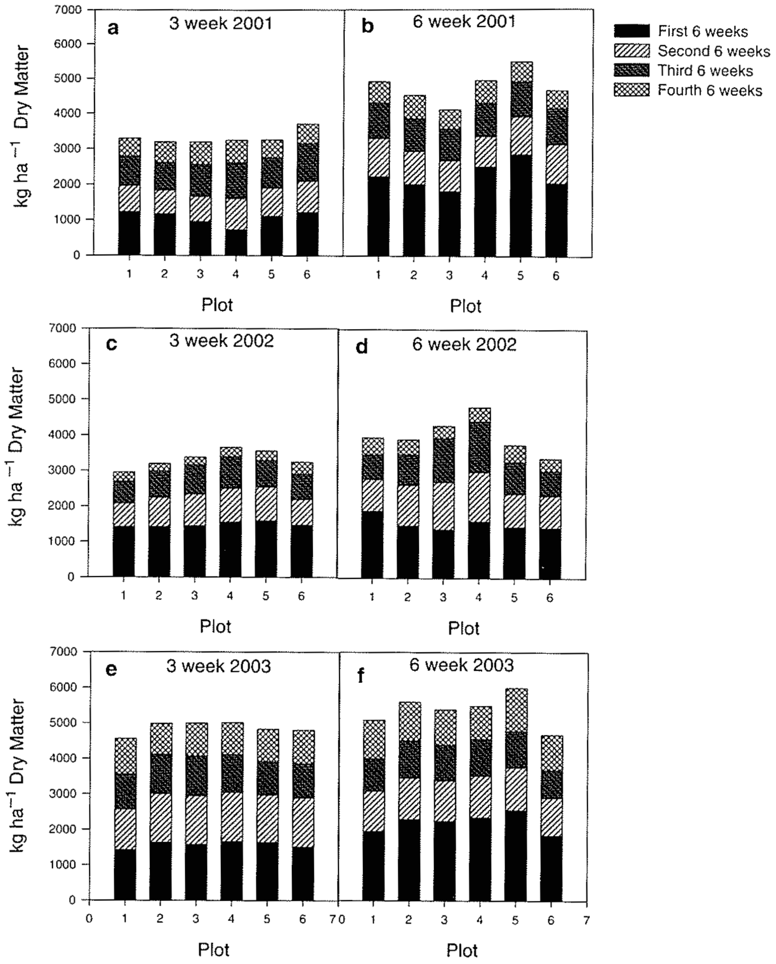

Figure 4.5 Dry matter (kg ha^{-1}) for strip locations for four 6-week periods from 2001 to 2003. Figures a, c, and e are the sum of two 3-week harvests. Each value is the average of three replications

Table 4.3 Average yield for harvest sites for 2001, 2002, 2003 and 3-year average. Each value is the average of four yearly harvests for three replications. Values in vertical columns followed by the same letter and not statistically different at $P < .05$

	Yield (kg ha^{-1})			
Site	2001	2002	2003	3 year
1	1027 a	864 b	1207 a	1032 a
2	966 a	867 a,b	1324 a	1059 a
3	915 a	958 a,b	1299 a	1057 a
4	1025 a	1059 a	1313 a	1132 a
5	1094 a	914 a,b	1353 a	1020 a
6	1049 a	826 b	1186 a	1021 a

Within vertical columns means with the same letter are not significantly different at the 0.05% level (Tuckey's HSD test)

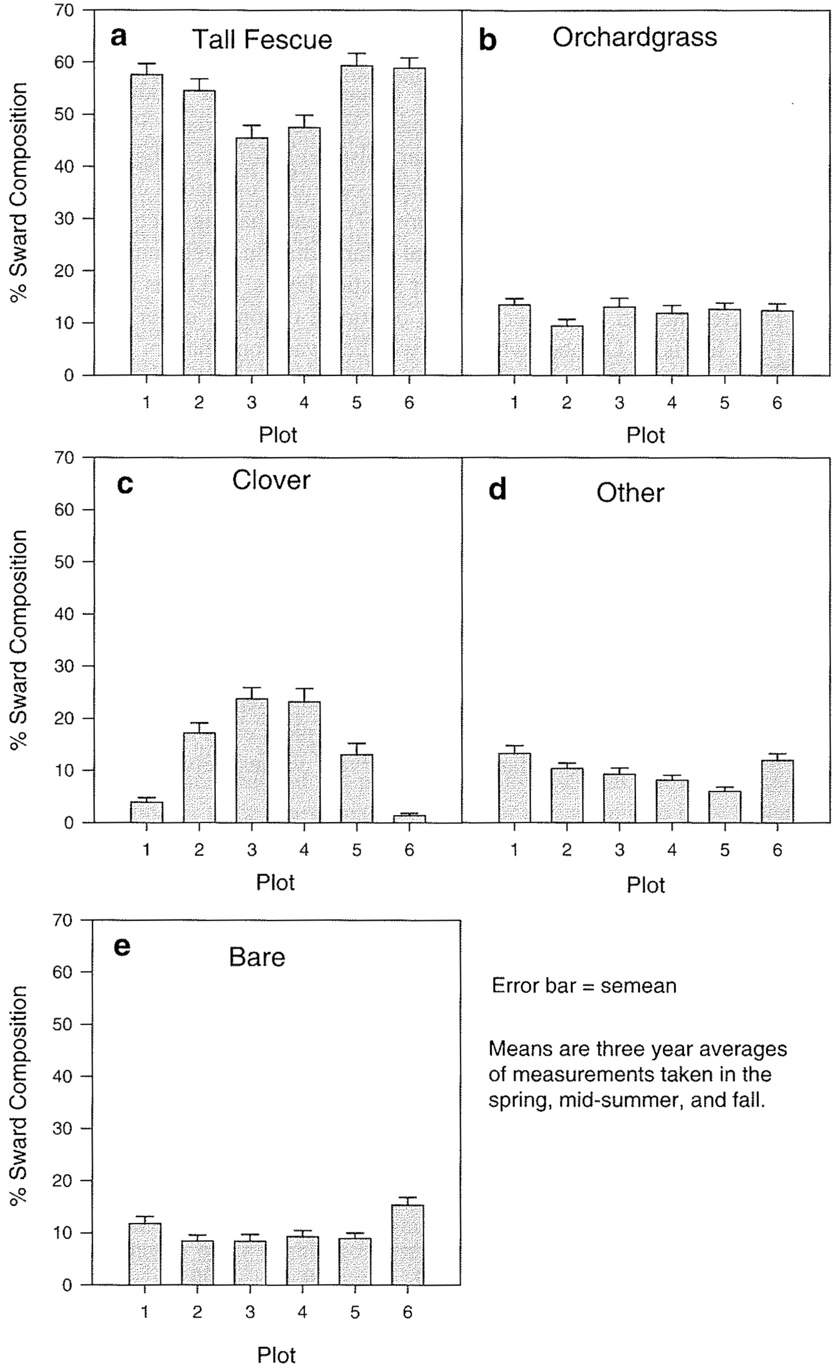

Figure 4.6 Botanical composition for plots relative to tree rows. Each bar represents the average of three determinations (spring, summer, and early autumn sampling) of 3 years and for three replications

Discussion and Conclusions

Temperate, deciduous silvopastures are dynamic seasonal production systems where PAR varies widely in time and space. For this site, daily PAR was nearly 90% of the seasonal maximum (at summer solstice) before trees began developing leaves, thus forages under trees experienced essentially unshaded conditions when the flush of spring growth occurred (Figure 4.7). Peak shading occurred at summer solstice. PAR then decreased with seasonal solar radiation levels until autumn equinox, at which time is was 60% of summer solstice levels, and trees began dropping leaves This resulted in the upper portion of forage canopies under trees receiving higher PAR levels in October when the weather was cool than in July or August when it was warmest. There was some shading from the small senesced leaves falling within the forage canopy but the effect of this on lower canopy PAR was not measured.

During the warmest summer months forages under trees experienced cooler soil temperatures, which is conducive to better growth for C3 grasses such as tall fescue. Feldhake (2001) found that surface soil temperatures during dry periods could be as much as 12 °C cooler under trees. Soil moisture was slightly lower under trees than in the alley centers. However, for most of the study period soil moisture levels were sufficient that this difference was not critical. A decrease in shade-site evapotranspiration demand may help compensate for lower soil moisture and facilitate forages maintaining a favorable tissue water balance for growth.

Total forage production did not differ between plots even though summer PAR varied by a factor of 5. Constant forage harvest values between plots differing widely in summer PAR is not proof that photosynthesis was constant. Shaded forages partition a lower percentage of their photosynthate into non-leaf structures than unshaded (Belesky, 2005). The result is that leaf elongation is maintained, or in some cases even slightly enhanced, even though photosynthesis is somewhat light limited. Cool season plants also utilize diffuse radiation more efficiently than direct beam (Sinclair et al. 1992) and in humid climates, cloud scattering produces substantial diffuse radiation. Feldhake (2001) found that under black locust, PAR levels were two times greater under 30% cloudiness than under clear sky conditions.

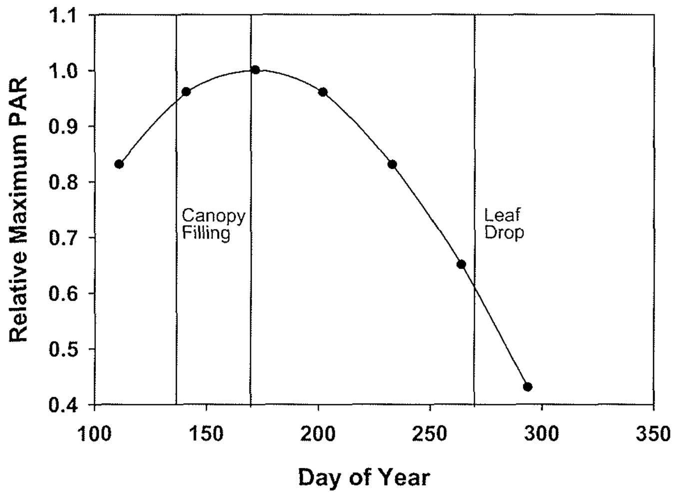

Figure 4.7 Relative maximum possible forage growing season PAR compared to summer solstice. The period of tree canopy development and initiation of leaf drop is indicated. Average daily PAR at this location was half of maximum due to cloudiness

Orchardgrass is somewhat more shade tolerant than tall fescue (Burner, 2003) thus, it was interesting to observe that there was no increase in orchard grass under the tree canopies compared to the alley center. Ladino clover (C3) is less shade tolerant than many C3 grasses and a decrease in clover, as a percentage of the canopy, was observed for plots under trees compared to the alley center. There was also an increase in bare patches under tree canopies even though this did not translate into lower total forage yield. This was probably because clover yields less per unit area than tall fescue so that the yield loss due to bare patches under trees was offset by decreased yield for areas dominated by clover.

Black locust trees planted in rows did not decrease total yield of forages within an existing pasture during growth years 9–11. Forages growing under tree canopies received as little as one fifth the PAR received by forages in alley centers during summer months. Soil temperature of plots under trees was about 2 °C cooler and slightly dryer than that of alley centers during midday. Tall fescue proved to be very plastic and able to grow well under widely varying conditions. Clover, however, thrived in alley centers but did not persist at the lowest PAR sites under tree rows. Black locust appears to be a reasonable choice for inclusion into hilly Appalachian pastures where silvopastoral systems are desired.

Acknowledgments We would like to thank C.E. Lynch for his assistance in collecting microclimate data. Names of instrument manufacturers were provided for reader information only and do not imply endorsement by USDA-ARS.

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Chapter 5
Light Intensity Effects on Growth and Nutrient-use Efficiency of Tropical Legume Cover Crops

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Introduction

In the tropics, plantation crops are established on newly cleared forest lands with a wide spacing between rows and within rows. For example, cacao (*Theobroma cacao*) on newly cleared forest lands is being planted with wide spacing of 1.2×1.2m to 5.0×5.0m (Wilson, 1999). Under such a planting pattern, the soil is unprotected during early plantation growth, and is subject to erosion and nutrient leaching. Planting a fast-growing cover crop in early stages of plantation crop establishment might help to reduce soil erosion and increase soil organic matter content, leading to restoration of soil fertility and productivity (Cunningham and Smith, 1961; Wood and Lass, 2001). In addition, cover crops are known to improve soil water-holding capacity, increase biological activities, suppress weed growth, and decrease effects of diseases and insects (Maesen and Somaatmadja, 1989; Blevins and Frye, 1993; Wessel and Maesen, 1997; Teasdale, 1998).

In cacao plantations, legume cover crops fix N and provide shade to early growing cacao and minimize the loss of soil by erosion (Wood and Lass, 2001). Beneficial effects of limited number of cover crops in improving growth and yield of cacao have been reported (Jorden and Opoku, 1966; Opoku, 1970; Wilson, 1999). Species such as *Calapogonium muconoides, Crotalaria striata, Flemingia macrophylla, Pueraria javanica, P. phaseoloides, Sesbania punctata, Tephrosia candida*, and *Tephrosia vogelii* have been used as cover crops (Wilson, 1999; Wood and Lass, 2001). Limited numbers of other valuable legume cover crops have been evaluated for their compatibility with cacao. Many legume cover crops such as joint vetch

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

(*Aeschynomene americana*), sunhemp/Indian hemp (*Crotalaria juncea* L.), crotalaria ochroleuca (*Crotolari orchroleuca*), showy crotolaria/crotalaria spectabilis (*Crotolaria spectabilis*), hairy indigo (*Indigofera hirsute L*), lab-lab (*Lablab purpureus*), sesbania(*Sesbania microcarpa*), Brazilian lucern/Brazilian stylo (*Stylosanthes guianensis*), and cow pea/Fejao caupi (*Vigna unguiculata*) are tolerant to high, prevailing tropical temperatures, and rainfall conditions, and adaptable to wide range of pH's that are common in the tropical soils (Duke, 1981; Wessel and Maesen, 1997). However, information is lacking of their suitability as cover crops and ability to grow in low light intensities in plantation crops such as cacao.

Solar radiation intensity and interception by plants are fundamental processes governing crop growth and yield. A close relationship between light interception and yield has been demonstrated for a large variety of plant species (Monteith, 1977). In tropical regions, incoming photosynthetically active radiation is around 1800µmol m^{-2} s^{-1} (Grace et al. 1998). Plantation crops, such as cacao, are sensitive to high light intensity and are therefore grown under various types of shade trees (Wood and Lass, 2001). For young cacao about 50% shade is optimum and amount of radiation observed at canopy level has been 800–900µmol m^{-2} s^{-1} (Wood and Lass, 2001). When cover crops are grown under plantation crops, growth of cover crops is influenced by the amount of photosynthetic photon flux density (PPFD) reaching the cover crop (Wilson, 1999). Canopies of shade trees and cacao together reduce the amount of PPFD at the cover crop canopy levels. In tropical forest depending on the leaf canopy density, understory plants receive around 2% of the PPFD that is received at the upper canopy levels, and understory crops also receive intermittently high levels of PPFD in sunflecks (Liang et al. 2001). Cover crop species that tolerate lower PPFD protect the soil longer in plantation crops and improve its fertility.

The legume cover crops chosen for this study have great potentials as suitable cover crops for cacao plantation, mainly because they sustain many of the prevailing abiotic stresses that are common in the tropical plantation crops. However, their ability to grow at low light intensity is unknown. The objective of our study was to evaluate the influence of low levels of PPFD on growth and nutrient uptake and use efficiency of nine tropical legume cover crops.

Materials and Methods

A growth chamber experiment was conducted at Beltsville Agricultural Research Center, Beltsville, Maryland, with a day temperature of 30°C at 65% relative humidity, and a night temperature of 28°C at 65% relative humidity. In South America, cacao is grown under such climatic conditions (Wood and Lass, 2001) and therefore we selected these temperature and humidity values to test the cover crops, mainly because these crops will be grown as an understory plants in cacao plantation. Plants were subjected to 14h of light and 10h of darkness daily. Plants were grown at two photosynthetic photon flux densities (PPFD) as light treatments: 200µmole m^{-2} s^{-1} and 400µmole m^{-2} s^{-1}. These selected light treatments represent about 10–20% of the PPFD received in the tropical region. Within the growth room, mini chambers were constructed with 2cm diameter PVC pipe and covered with various layers of plastic shade cloth to achieve desired PPFD.

Nine annual erect shrub-type leguminous cover crops were used in this study (Table 5.1). These include: Joint Vetch (*Aeschynomene americana*), Sunhemp/Indian hemp (*Crotalaria juncea* L.), Crotalaria ochroleuca (*Crotolari orchroleuca*), Showy crotolaria/Crotalaria spectabilis (*Crotolaria spectabilis*), Hairy indigo (*Indigofera hirsute L*), Lab-lab (*Lablab purpureus*), Sesbania(*Sesbania microcarpa*), Brazilian lucern/Brazilian stylo (*Stylosanthes guianensis*), and Cow pea/Fejao caupi (*Vigna unguiculata*). Twenty seeds of each legume cover crop were planted in black plastic pots containing 2kg of perlite/sand/ promix (2:2:1 volume basis) with adequate bottom drainage. Osmocoat (18-6-12, Scotts, Marysville, OH), triple super phosphate, urea, $CaSO_4$. dolomitic lime, and Scotts micromax were mixed with growth medium to provide 600N, 600P, 240K, 1012Ca, 309Mg, 500S, 119Fe, 0.7B, 17.5Mn, 7.0Cu, 7.0Zn, and 0.35Mo mg kg^{-1}. Every other day pots were weighed and desired amount of deionized water was added to maintain growth medium water level at field capacity. Amount of water held at field capacity was determined by placing saturated potting mixture in cylinder and allowing it to drain for 48h and moisture content was determined by drying soil at 110°C until constant weight is reached. Amount of water held by the growth mixture was considered as field capacity moisture content.

On the 10th day of growth, plants in each pot were thinned to keep two plants per pot for larger growing species and seven plants per pot for smaller growing species. Seedlings that were removed with root intact were used for determination of initial growth (shoot dry weight, leaf area, stem height, root length, and root dry weight) and nutrient uptake parameters were recorded (baseline harvest). After 45 days of growth all remaining plants were harvested, and roots and shoots were separated and washed with deionized water. Leaves were separated from stem and leaf area was determined with Li-Cor model 300 leaf area meter (Li-Cor Inc., Lincoln, NB) and stem height was recorded. Root and shoots were dried at 70°C for 5 days and dry weight was recorded. Shoot samples were ground to pass a 0.55mm mesh sieve. Chemical analysis of the shoot samples was done at the A&L Southern Agricultural Lab, Pompano Beach, FL, by adapting modified methods suggested by Wolf (1982). Plant samples were wet digested in concentrated sulfuric acid and 30% hydrogen peroxide. Gilford STASAR II spectrophotometer was used to determine N and P, and Perkin Elmer Analyst 400 Atomic Absorption Spectrophotometer was used to determine the K, Ca, Mg, and Na. Plant samples were wet digested in muffle furnace at 600°C with magnesium nitrate and dissolved in 1:1 HCl, and S concentration was determined by colorimetric method by use of Gilford STASAR II spectrophotometer.

The following growth and nutrient uptake parameters were determined.

Specific leaf area (SLA, cm^2/g) = [Total leaf area, cm^2/Total leaf dry wt, g]
Leaf area ratio (LAR, cm^2/g) = [Total leaf area, cm^2/Shoot + Root dry wt, g]
Leaf mass/Unit leaf area (LMA, g/cm^2) = [1/SLA]
Root/Shoot ratio(R/S) = [Wr/Ws], where Wr is root weight and Ws is shoot weight

Table 5.1 Shoot, root, and leaf growth parameters, RGR and NAR of leguminous cover crops as influenced by varying PPFD[a]

Species	PPFD[b]	Shoot wt g/plant	Root wt g/plant	R/S	RGR $\times 10^2$	NAR $\times 10^4$	LA cm^2/plant	SLA cm^2/g	LAR cm^2/g	LMA g/cm^2
Joint Vetch	L_1	0.67f–h	0.06b	0.08a–c	15b	10.4d	105.68f	250.48ef	147.16f–h	4.0cd
	L_2	1.33e–g	0.15b	0.11a–c	16b	16.1c	149.38ef	175.74g	100.53hi	5.7b
Sunhemp	L_1	1.39d–f	0.10b	0.07a–c	10d	4.5gh	338.52de	406.61b	241.63bc	2.5f–h
	L_2	4.62a	0.47a	0.10a–c	13c	9.1de	762.07b	309.52de	148.82e–h	3.3c–g
Crotoloria ochro	L_1	0.56gh	0.04b	0.08a–c	14c	6.9e–g	119.45ef	338.14cd	199.57b–e	3.0d–g
	L_2	1.37d–f	0.15b	0.11a–c	15b	10.9d	209.11ef	266.26ef	141.24gh	3.9c–e
Showy crotolaria	L_1	0.79e–f	0.12b	0.16a	13c	5.2gh	225.92ef	396.78bc	245.93bc	2.5f–h
	L_2	1.68d	0.24ab	0.14ab	13c	5.4f–h	484.27cd	405.71b	251.15d	2.5gh
Hairy indigo	L_1	0.54h	0.02b	0.03c	15b	8.7d–f	97.93f	287.54d–f	176.07d–g	3.5c–f
	L_2	1.48de	0.08b	0.06bc	17a	11.9d	227.35ef	243.53f	148.31e–h	4.1c
Lab–lab	L_1	3.31bc	0.48a	0.15ab	10de	3.0h	1223.62a	587.36a	324.45a	1.7h
	L_2	3.17c	0.14b	0.05c	10de	3.0h	1134.15a	599.21a	337.88a	1.7h
Sesbania	L_1	1.90d	0.21ab	0.11a–c	16b	24.1b	133.46ef	134.46g	68.10i	7.8a
	L_2	3.94a–c	0.46a	0.12a–c	18a	35.6a	224.03ef	123.12g	50.90i	8.1a
Brazilian stylo	L_1	0.09h	0.01b	0.05c	11d	5.9e–h	18.06f	349.16b–d	197.51c–f	2.9e–g
	L_2	0.28h	0.01b	0.05c	13c	6.6e–g	58.75f	306.19de	203.86b–d	3.3c–g
Cowpea	L_1	3.47bc	0.11b	0.03c	9e	4.9gh	654.93bc	397.05bc	181.73d–g	2.5f–h
	L_2	4.08ab	0.15b	0.04c	9e	6.6e–g	577.95bc	398.13bc	135.62	2.5f–g
Mean	L_1	1.41	0.13	0.08	13	8.2	324.17	349.73	198.02	3.4
	L_2	2.44	0.21	0.09	14	11.7	425.23	314.16	168.70	3.9
Significance										
Species (S)		**	*	*	**	**	**	**	**	**
PPFD (P)		**	NS	NS	**	**	*	**	**	**
S × P		**	NS	NS	**	**	NS	NS	NS	NS

Values within a column followed by the same letter are not significantly different ($P < 0.05$, Tukey's test).

*,**Significant at 0.05 and 0.01 levels of probability, respectively.

[a] RGR = Relative growth rate, g/g/d; NAR = Net assimilation rate, g/cm²/d; R/S = Root/Shoot ratio; LA = Leaf area; SLA = Specific leaf area; LMA = [Leaf mass/Unit leaf area].

[b] L_1 = PPFD (Photosynthetic photon flux density) of 200 μmol m^{-2} s^{-1}; L_2 = PPFD of 400 μmol m^{-2} s^{-1}.

Relative Growth Rate (RGR) = $[\ln (Wt_2/Wt_1)/(T_2-T_1)]$, where Wt is total weight (shoots + root), T is time interval in days, and 1 and 2 refers to initial and final harvest

Net assimilation rate (NAR) = [RGR/LAR]

Nutrient influx (IN) = $[(U_2-U_1)/(T_2-T_1)]\times[(\ln Wr_2-\ln Wr_1)/(Wr_2-Wr_1)]$, where U refers to elemental content of shoot (μmol/plant) and T is time in seconds, subscripts 1 and 2 refer to initial and final harvest time

Nutrient transport (TR) = $[(U_2-U_1)/(T_2-T_1)]\times[(\ln Ws_2-\ln Ws_1)/(Ws_2-Ws_1)]$

Nutrient use efficiency ratio (ER) = [mg of Ws/mg of any given element in shoot]

Treatments were replicated three times and data were subjected to analysis of variance using general linear model (GLM) procedures of SAS (Ver. 8, SAS Institute, Cary, NC).

Results and Discussion

Root and Shoot Growth

At both PPFD levels significant variation was observed in growth parameters among different plant species (Table 5.1). Variation in shoot weight was 0.09–3.31 g $plant^{-1}$ at low PPFD and 0.28–4.62 g $plant^{-1}$ at high PPFD. When averaged across plant species, shoot weight was 1.41 g $plant^{-1}$ at low light intensity and 2.44 g $plant^{-1}$ at high light intensity. Overall increase in shoot dry weight was 73% at higher light intensity compared to lower light intensity. Similarly, overall increase in root dry weight was 62% at higher light intensity compared with lower light intensity. This indicates that shoot dry weight was more sensitive to light intensity than root weight. Overall, root weight was significantly correlated with shoot weight ($r=0.56$, $P<0.01$) indicating, a mutually beneficial effects of increasing light intensity on roots and shoots on each other.

Cowpea, sesbania, lab-lab, and sunhemp produced higher shoot and root dry weights at 200 and 400 μmol m^{-2} s^{-1} of PPFD compared to other species. Brazilian stylo and hairy indigo produced lowest shoot and root weight at both the PPFD. The difference in growth and development among different plant species is associated with their complex genetic, physiological, and morphological determinants, which include photosynthesis, respiration, and water and mineral uptake (Krizek et al. 1985). Leaf area was also significantly correlated with root dry weight ($r=0.44$, $P<0.001$) and shoot weight ($r=0.72$, $P<0.01$).

Improvement in most of the growth parameters at higher light intensity was associated with enhanced photosynthesis, which leads to increased dry matter accumulations (Fageria, 1992; Fageria et al. 1997). Schittenhelm et al. (2004) reported that the economic yield of any crop is a function of the amount of light energy absorbed by the green foliage, the efficiency of the foliage to use the energy captured for biomass production, and the partitioning of the crop biomass to the harvested plant part. Similarly, Whitman et al. (1985) reported that dry matter yield of crops increases in a quadratic fashion with increasing intercepted radiation.

For all legumes evaluated, plant species × PPFD interactions were significant for shoot dry weight, relative growth rate (RGR) and net assimilation rate (NAR, a measure of the efficiency of plant leaves to produce dry matter), indicating that these plant growth parameters can be manipulated with the variation of PPFD intensities in favor of higher yield (Table5.1). The overall improvement in relative growth rate was 8% at 400 μmol m^{-2} s^{-1} of PPFD compared with 200 μmol m^{-2} s^{-1} of PPFD (Table5.1). Similarly, increase in net assimilation rate was 43% with the PPFD of 400 μmol m^{-2} s^{-1} compared to 200 μmol m^{-2} s^{-1} of PPFD. Data in Table 5.1 show that among nine crop species, sesbania had the highest NAR at low as well as at high PPFD and lab-lab had lowest NAR values at both PPFD levels. The lower NAR rate of lab-lab may be due to its self shading of leaves and reduced photosynthetic efficiency of older leaves.

Nutrient Uptake and Use Efficiency

Uptake of all the macronutrients was significantly influenced by species, PPFD and species × PPFD interactions (Table 5.2). Variations in nutrients uptake were related to differences in dry matter accumulation between species. For example, Brazilian stylo produced lowest dry matter yield and had the lowest nutrient uptake. Similarly, sunhemp and cowpea produced higher dry matter yields and accumulated higher nutrient levels. Nutrient uptake was significantly correlated with shoot dry weight. The correlation values were: N (0.99, $P<0.01$), P (0.99, $P<0.01$), K (0.97, $P<0.01$), Ca (0.91, $P<0.01$), Mg (0.91, $P<0.01$), S (0.88, $P<0.01$) and Na (0.65, $P<0.01$). Such relationship clearly shows the significance of shoot demand on nutrient uptake.

Differences in nutrient uptake and yield among species have been related to differences in absorption, translocation, shoot demand, and dry matter production potentials per unit of nutrient absorbed (Baligar et al. 2001; Gerloff and Gabelman, 1983; Vose, 1984). Averaged across nine crop species, uptake of all the macronutrients was higher at higher PPFD. Furthermore, across crop species and light intensity, uptake of nutrient was in the order of N > K > Ca > P > S > Mg > Na. Fageria et al. (1997) reported similar trends in macronutrient uptake by legume crops. Most of the soluble N in well-drained cultivated soils is present in the nitrate form. These results also suggest that at high PPFD legume cover crops have high N requirement, therefore use of cover crops could lower the buildup of N in soil thereby reduce its leaching. Crop residue from these crops could also supply substantial amount of N to succeeding or companion plantation crops.

Nutrient efficiency ratio (mg shoot weight produced/mg nutrient accumulated in the shoot) of all the macronutrients was significantly influenced by crop species (Table 5.3). However, PPFD had a significant influence only for nutrient efficiency ratios of N, Na, K, and Mg. Crop species × PPFD interaction was significant for all

Table 5.2 Influence of PPFD on uptake of macronutrients in different species of leguminous cover crops

Species	PPFD[a]	N	P	S	Na mg plant^{-1}	K	Ca	Mg
Joint Vetch	L_1	29.81fg	8.83d–g	4.39g–i	0.25ef	19.13d–g	10.45e–h	2.72f–h
	L_2	58.09d–f	15.12d	7.47e–i	0.18f	34.49d–f	19.03d–f	5.61d–f
Sunhemp	L_1	84.12de	16.02d	15.37c–e	3.00bc	41.54c–e	21.40de	5.14d–g
	L_2	219.89a	19.45a	38.75a	11.34a	11.60ab	68.26a	20.80a
Crotoloria ochro	L_1	33.48fg	6.14e–g	6.04f–i	0.81d–f	17.49d–g	7.42f–h	2.08gh
	L_2	64.51d–f	15.37d	12.60c–g	1.51c–f	37.02de	20.10d–f	6.49de
Showy crotolaria	L_1	44.05e–g	6.07e–g	8.42d–i	0.56ef	21.13d–g	15.15e–h	2.47f–h
	L_2	94.67d	13.55de	16.46cd	1.05d–f	43.78cd	32.32cd	5.40d–g
Hairy indigo	L_1	22.89fg	3.23fg	2.79hi	0.13f	16.56fg	11.28e–h	1.93gh
	L_2	65.58d–f	10.77d–f	13.85c–f	0.50ef	41.37de	35.27c	6.74de
Lab-lab	L_1	155.93bc	35.12c	19.60bc	0.47ef	115.34ab	15.30ab	8.47cd
	L_2	140.03c	35.37c	11.13d–g	0.32ef	104.58b	41.13c	6.85de
Sesbania	L_1	93.02d	15.48d	8.97d–h	0.93d–f	68.04c	16.40e–g	4.69e–g
	L_2	197.78ab	39.10bc	20.60bc	2.54cd	117.24ab	37.50c	11.22c
Brazilian stylo	L_1	3.50g	0.80g	0.56i	0.06f	2.72g	1.43h	0.21h
	L_2	10.31g	2.06g	1.40hi	0.06f	7.89fg	4.50gh	0.63h
Cowpea	L_1	160.15bc	36.98c	24.81b	1.99c–e	138.39a	44.59bc	16.95b
	L_2	181.58a–c	45.53ab	25.55b	4.36b	124.22ab	40.41c	18.60ab
Mean	L_1	69.66	14.30	10.11	0.91	48.93	15.94	4.96
	L_2	114.72	25.15	16.42	2.43	58.02	33.17	9.15
Significance								
Species (S)		**	**	**	**	**	**	**
PPFD (P)		**	**	**	**	**	**	**
S × P		**	**	**	**	**	**	**

Values within a column followed by the same letter are not significantly different ($P < 0.05$, Tukey's test).

*,**Significant at 0.05 and 0.01 levels of probability, respectively.

[a] L_1 = PPFD (Photosynthetic Photon Flux Density) of 200 μmol m^{-2} s^{-1}; L_2 = PPFD of 400 μmol m^{-2} s^{-1}.

Table 5.3 Influence of PPFD on nutrient efficiency ratio of macronutrients in different species of leguminous cover crops

Species	PPFD[a]	N	P	S	Na	K	Ca	Mg
		mg shoot mg element in shoot^{-1}						
Joint Vetch	L_1	22.7b,c	75.3f	152.0d–g	2777.8b	34.9c–f	64.4b–d	246.5d–f
	L_2	23.0b,c	89.7de	179.5b–d	8333.3a	38.8a,b	70.5b	238.5d–f
Sunhemp	L_1	17.6e,f	85.6ef	102.5gh	842.1d,e	32.4e–g	64.9b–d	270.4c–e
	L_2	21.3b–d	93.5de	120.2e–h	427.7e	40.7a	68.0b,c	222.3e,f
Crotoloria ochro.	L_1	16.9f	91.2de	93.3h	756.2e	32.2f–h	75.5b	268.5c–e
	L_2	21.5b–d	89.4d–f	107.6fh–	970.7de	36.9c,d	67.6b,c	210.1f
Showy crotolaria	L_1	17.8e,f	129.8bc	93.4h	1476.2c–e	37.7a–c	52.4c,d	321.1b,c
	L_2	17.7e,f	124.0bc	102.1g,h	1944.4c–e	38.3a–c	52.0c–e	311.2b,c
Hairy indigo	L_1	23.7b	168.2a	218.9b	4444.4b	32.7e–g	48.2d,e	285.5c,d
	L_2	22.6b,c	136.4b	108.8e–h	3055.6bc	36.0b–e	42.0e	219.1e,f
Lab-lab	L_1	21.3b–d	93.9de	196.9b–d	8333.3a	28.7h–j	61.8b–d	411.2a
	L_2	22.9b,c	90.9de	286.1a	10000.0a	30.3g–i	77.5b	463.1a
Sesbania	L_1	20.9c,d	132.2b	214.0b,c	2777.8b–d	28.3i,j	113.8a	427.1a
	L_2	20.0d,e	100.7d	195.3b–d	1619.0c–e	33.9d–g	104.8a	353.3b
Brazilian stylo	L_1	26.5a	116.3c	163.9b–e	1428.6c–e	34.0e–f	64.9b–d	434.8a
	L_2	26.8a	135.9b	198.9b–d	4444.4b	35.0c–f	62.0b–d	442.5a
Cowpea	L_1	21.7b–d	94.1d,e	147.9d–h	1809.5c–e	25.1j	79.6b	210.4f
	L_2	22.5b–d	89.6d,e	160.8c–f	988.1d,e	32.9e–g	108.1a	221.3e,f
Mean	L_1	21.0	109.6	153.6	2738.4	31.8	69.5	330.6
	L_2	22.1	105.6	162.1	3531.5	35.9	69.2	297.9
Significance								
Species (S)		**	**	**	**	**	**	**
PPFD (P)		*	NS	NS	*	**	NS	*
S × P		*	**	**	**	*	NS	*

Values within a column followed by the same letter are not significantly different ($P < 0.05$, Tukey's test).

*, **Significant at 0.05 and 0.01 levels of probability, respectively.

[a] L_1 = PPFD (Photosynthetic Photon Flux Density) of 200μmol m^{-2} s^{-1}; L_2= PPFD of 400μmol m^{-2} s^{-1}.

the macronutrient efficiency ratios with the exception of Ca. Significant crop species × PPFD interaction suggests that crop variation in macronutrient utilization depends on light intensity. Across plant species and PPFD levels, nutrient utilization efficiency ratios were in the order of Na > Mg > S > P > Ca > N. Hence, legume cover crops evaluated in this study require maximum amounts of N and minimum amounts of Na to produce equal amounted of dry matter. Plants that have high ER values for essential nutrients might produce well when grown on infertile soil where supply of nutrients is limited. Interspecific variation in mineral uptake and utilization in various plant species is well documented (Baligar et al. 2001; Baligar and Fageria, 1997; Gerloff and Gabelman, 1983; Vose, 1984). Variations in nutrient utilization within and between plant species are known to be under genetic and physiological control but are modified by plant interactions with environmental variables (Baligar and Fageria, 1997; Baligar et al. 2001).

Nutrient Influx and Transport

Macronutrient influx into roots was significantly affected by crop species; however, PPFD had no effect on nutrient influx (Table 5.4). At both PPFD's, hairy indigo had maximum influx of macro nutrients, and showy crotalaria had the minimum influx of N, P, K, and Mg. Overall, nutrient influx in to the root was in the order of N > K > Ca > P > S > Mg > Na.

Transport of all the micronutrients was significantly affected by crop species (Table 5.4). Whereas, PPFD significantly affected the transport of P, Ca, and Mg only. Similarly, crop species × PPFD interactions were significant for transport of P, S, Ca, and Mg. Root morphological parameters such as length, surface area, volume dry weight (Hackett, 1969; Baligar et al. 2001), and physiological conditions of plants are known to affect plant nutrient uptake, influx, and transport (Drew et al. 1969; Pitman, 1972). Differences in nutrient influx and transport among plant species have been related to differences in shoot demand per unit of nutrient absorbed (Gerloff and Gabelman, 1983; Vose, 1984; Baligar and Fageria, 1997).

Conclusions

Nine cover crop species tested in this experiment expressed significantly different growth parameters and nutrient uptake, influx, transport, and utilization efficiency at different PPFD's. Hence, it is possible to select cover crop species, which may be suitable for different plantation crops with varying amounts of shade in improving soil fertility and conserving soil and water resources. Maximum growth of root, shoot, relative growth rate, and net assimilation rate, uptake of N, P, S, Na, K, Ca, and Mg was achieved at PPFD of 400μmole m^{-2} s^{-1}. Nutrient utilization efficiency was in the order of Na > Mg > S > P > Ca > N. Nutrient uptake significantly correlated

Table 5.4 Influence of PPFD on influx of macronutrients in different species of leguminous cover crops

Species	PPFD[a]	N	P	S	Na	K	Ca	Mg
		nmole g root^{-1} s^{-1}						
Joint Vetch	L_1	59.6b–d	8.0a	3.8b,c	0.3e–g	13.8d–f	7.3b–d	3.1c–e
	L_2	49.5c,d	5.8a–d	2.8b,c	0.1g	10.5d–f	5.7b–d	2.8d,e
Sunhemp	L_1	54.3c,d	4.8a–d	4.3bc	1.1a,b	10.2d–f	4.9b–d	2.0e
	L_2	45.9c,d	4.7a–d	3.5b,c	1.4a	8.5e,f	5.0b–d	2.5d,e
Crotoloria ochro.	L_1	74.6a–d	6.2a–d	6.0b	1.1a–c	14.0d–f	5.9b–d	2.7d,e
	L_2	52.3c,d	5.6a–d	4.5b,c	0.8b–d	10.8d–f	5.8b–d	3.0c–e
Showy crotolaria	L_1	40.2d	2.5c,d	3.4b,c	0.3e–g	7.1f	4.9b–d	1.3d
	L_2	41.8c,d	2.7c,d	3.2b,c	0.3e–g	6.9f	5.0b–d	1.4d
Hairy indigo	L_1	101.1a,b	6.4a–d	5.4b,c	0.3e–g	26.2a,b	17.4a	4.9a–c
	L_2	107.8a	8.0a	10.0a	0.5d–g	24.8a–c	20.1a	6.4a
Lab-lab	L_1	86.0a–c	8.5a	5.7bc	0.2fg	20.9a–d	10.9b	2.9de
	L_2	59.1b–d	6.7a–c	1.9c	0.1g	16.1b–f	6.1b–d	1.6e
Sesbania	L_1	50.9c,d	3.7b–d	2.3b,c	0.3e–g	13.4d–f	3.4c,d	1.5e
	L_2	58.6b–d	5.2a–d	2.7b,c	0.5e–g	12.4d–f	3.9c,d	1.9e
Brazilian stylo	L_1	54.8c,d	5.6a–d	3.8bc	0.6c–f	15.4c–f	7.8b–d	1.9e
	L_2	65.2a–d	5.8a–d	3.8bc	0.2f,g	17.9a–e	9.9b,c	2.3d,e
Cowpea	L_1	85.1a–d	8.8a	5.5bc	0.6b–f	26.9a	8.1b–d	5.1ab
	L_2	67.4a–d	7.6a,b	4.0b,c	1.0a–d	16.7a–f	4.9b–d	3.9a–d
Mean	L_1	67.4	6.1	4.5	0.5	16.4	7.8	2.8
	L_2	60.9	5.8	4.3	0.5	13.9	7.4	2.9
Significance								
Species (S)		*	*	*	**	**	**	**
PPFD (P)		NS	NS	NS	NS	NS	NS	NS
S × P		NS	NS	NS	NS	NS	NS	NS

Values within a column followed by the same letter are not significantly different ($P < 0.05$, Tukey's test).

*,**Significant at 0.05 and 0.01 levels of probability, respectively.

[a] L_1 = PPFD (Photosynthetic Photon Flux Density) of 200 µmol m^{-2} s^{-1}; L_2= PPFD of 400 µmol m^{-2} s^{-1}.

Table 5.5 Influence of PPFD on transport of macronutrients in different species of leguminous cover crops

Species	PPFD[a]	N	P	S	Na	K	Ca	Mg
		nmole g shoot^{-1} s^{-1}						
Joint Vetch	L_1	5.66c,d	0.77a	0.37c,d	0.03e–h	1.31c,d	0.70c	0.30c,d
	L_2	5.85b–d	0.68b	0.33c–f	0.01f–h	1.24d,e	0.67c,d	0.32b,c
Sunhemp	L_1	5.30d	0.47e,f	0.41b,c	0.11b	1.00g,h	0.48e–g	0.19g
	L_2	5.31d	0.54d,e	0.41bc	0.17a	0.99g,h	0.58d,e	0.29c,d
Crotoloria ochro.	L_1	6.79a,b	0.56c,d	0.54a	0.10b,c	1.28d	0.53e,f	0.24e,f
	L_2	5.91b–d	0.64bc	0.51a,b	0.09b–d	1.23d,e	0.66c,d	0.35a,b
Showy crotolaria	L_1	5.99b–d	0.37h	0.50a,b	0.05d–g	1.01g	0.71c	0.19g
	L_2	6.33b,c	0.41f–h	0.48a,b	0.04e–h	1.05f,g	0.75c	0.21f,g
Hairy indigo	L_1	5.59c,d	0.36h	0.29e–g	0.02e–h	1.45c	0.96b	0.27d,c
	L_2	6.47b,c	0.48e,f	0.59a	0.03e–h	1.46b,c	1.21a	0.38a
Lab-lab	L_1	3.85e	0.39g,h	0.20g,h	0.01g,h	1.03f,g	0.47f–h	0.12i,j
	L_2	3.68e	0.42f–h	0.12h	0.00h	1.00g,h	0.38h,i	0.10j
Sesbania	L_1	6.42b,c	0.47e–g	0.28e–g	0.04e–h	1.70a	0.42g–i	0.18g,h
	L_2	7.67a	0.69b	0.35c–e	0.06c–e	1.62a,b	0.51e–g	0.25e
Brazilian stylo	L_1	3.48e	0.35h	0.24e–g	0.04e–h	0.98g,h	0.50e–g	0.12i,j
	L_2	4.26e	0.38h	0.25e–g	0.02f–h	1.17d–f	0.65c,d	0.15h,i
Cowpea	L_1	3.46e	0.36h	0.23f–h	0.03e–h	1.09e–g	0.33i,j	0.21f,g
	L_2	3.42e	0.38h	0.20g,h	0.05d–f	0.85h	0.26j	0.20g
Mean	L_1	5.17	0.46	0.34	0.03	1.21	0.57	0.20
	L_2	5.43	0.51	0.36	0.04	1.14	0.63	0.25
Significance								
Species (S)		**	**	**	**	**	**	**
PPFD (P)		NS	**	NS	NS	NS	**	**
S × P		NS	**	**	NS	NS	**	**

Values within a column followed by the same letter are not significantly different ($P < 0.05$, Tukey's test).

*,**Significant at 0.05 and 0.01 levels of probability, respectively.

[a] L_1 = PPFD (Photosynthetic Photon Flux Density) of 200 µmol m^{-2} s^{-1}; L_2 = PPFD of 400 µmol m^{-2} s^{-1}.

with shoot dry weight in the order of N = P > K > Ca = Mg > S > Na. Hence, it can be concluded that N is the most yield limiting nutrient and Na is the least yield limiting nutrient for cover crops evaluated in this study. Cowpea, sesbania, lab-lab, and sunhemp produced good growth and higher nutrient uptake than other legumes at lower as well as at higher PPFD. Hence, these crop species appears to be suitable cover crops for tropical plantations crops with low PPFD.

Acknowledgments We thank S. Faulkner and J. Mascio for excellent technical support, J. Fisher for statistical analysis and Charles D. Foy, for critical comments. We thank following seed suppliers. Seeds of sunhemp, crotalaria ochroleuca, showy crotalaria, and lab-lab were received from Pirai seed company Av. Cassio paschoals Pado Vam; No 333, Piracicaba-SP Brazil; seeds of cowpea were received from Dr. Corival da Silva Embrapa Rice and Bean center GO Brazil; seeds of Brazilian style were received from Globo rural seed company, Av. Castello Branco 2177 Set Combra, Goania GO Brazil; seeds of joint vetch and hairy indigo were received from Adams-Briscoe Seed Co, Jackson GA and seeds of susbania were received from Dr Y. Li TREC – University of Florida, Homestead FL. Mention of trademark, proprietary product, or vender does not constitute a guarantee or warranty of the product by the U. S. Dept. of Agriculture and does not imply its approval to the exclusion of other products or venders that also may be suitable.

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Chapter 6

Interspecific Competition in a Pecan-cotton Alley-cropping System in the Southern United States: Is Light the Limiting Factor?

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Introduction

The manner in which light is intercepted by crop canopies and converted to structural dry matter can significantly affect primary production at a given site. A number of authors have investigated plant performance under different environmental conditions, including different levels of light, in alley cropping and similar agroforestry systems (Azam-ali et al. 1990; Monteith et al. 1991; Rosenthal and Gerik, 1991; Heitholt et al. 1992; Chirko et al. 1996; Gillespie et al. 2000; Jose et al. 2000). These studies have revealed strong linear relationships between photosynthetically active radiation (PAR, 400–700 nm) and dry matter production.

Plants that develop under low levels of PAR such as in agroforestry systems grow and develop differently than plants grown under full sun (Monteith et al. 1991; Lambers et al. 1998). The amount of intercepted PAR becomes the major determinant of biomass production when belowground resources are not limiting. This relationship has been conceptualized as the time integrated product of three factors (Monteith et al. 1991):

$$W = \int \varepsilon . i . Q \, dt \qquad (6.1)$$

where W is crop biomass (Mg ha^{-1}), ε is the radiation use efficiency (RUE), amount of biomass produced per absorbed light, i is the incident PAR intercepted by the canopy (MJ m^{-2}), and Q is the PAR incident at the top of the canopy (MJ m^{-2}). Light interception by plants has been shown to be affected by several factors

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(Beer et al. 1998; Bellow and Nair, 2003). These factors include leaf area, spatial distribution of leaves, crown height, and diameter among others.

Crop growth and development in alley-cropping systems depend on the intensity and availability of light. As such, how much light is captured and how efficiently it is used to create dry matter must be considered in the design and management of alley-cropping systems. Understanding the temporal and spatial variations in light transmittance and subsequent crop production is of great importance in this context. Hence, the objectives of this study were to (1) quantify the spatial and temporal distribution of light in an alley-cropping system involving pecan (*Carya illinoensis* K. Koch) and cotton (*Gossypium hirsutum* L.) and (2) determine its effect on the productivity of cotton. Our primary hypothesis was that cotton with its characteristic C_3 photosynthetic pathway would perform well under shade if light levels in the alleys were above the light saturation point and belowground competition for water and nutrients was alleviated. We further hypothesized that cotton grown in alley cropping might exhibit higher RUE than that of monoculture cotton due to competition for light between system components.

Materials and Methods

Study Area

The study was conducted in a 50-year-old pecan orchard converted into an alley-cropping system, located in Jay, Florida, USA (30°47 N, 87°13 W). The climate is considered temperate with moderate winters and hot humid summers. The soil is classified as a Red Bay sandy loam and described as a fine loamy, siliceous, thermic Rhodic Paleudult.

The pecan trees were planted at a uniform spacing of 18.3 m and remained under grass cover for 29 years until the initiation of the current study. Ten plots were established within the orchard and arranged into five blocks using a randomized complete block design in spring 2001. Each plot, which consisted of two rows of trees oriented in a north–south direction, was 27.4 m long and 18.3 m wide, with a practical cultivable width of 16.2 m, and was separated from its adjacent plot by a buffer of the same dimensions. Each block was randomly divided into a barrier plot and a non-barrier plot. Barrier plots were subjected to a root pruning treatment in which a trenching machine was used to dig a 0.2 m wide and 1.2 m deep trench along both sides of the plot at a distance of 1.5 m from the trees to separate root systems of pecan and cotton. A double layer of 0.15 mm-thick polyethylene sheeting was used to line the ditch prior to mechanical backfilling. The barrier plots (referred to as barrier treatment or barrier plants) thus served as the tree root exclusion treatment, preventing interaction of tree and cotton roots, while the non-barrier plots (referred to as non-barrier treatment or non-barrier plants), which did not receive this treatment, served as the tree-crop competition treatment. Monoculture plots (referred to as monoculture treatment or monoculture plants) were also established to compare production with barrier and non-barrier treatments (Allen, 2003; Wanvestraut et al. 2004).

Sixteen rows of cotton, 1 m apart, were planted in each alley. Cotton (DP458/RRvariety) was planted in a north–south orientation on 16 May 2001 and 13 May 2002 after disking the alleys.

PAR and Radiation Use Efficiency

Two 0.8 m Decagon Ceptometers (Decagon, Devices, Inc., Model SF-80, Pullman, WA), consisting of 80 PAR sensors with each sensor placed at a 1 cm interval, were used to measure incoming, transmitted, and reflected PAR (400–700 nm) in the alleys. Incoming PAR (Q_i) was measured right above the cotton canopy. Diurnal transmission of incoming radiation to cotton plants at rows 1, 4, 8, 13, and 16 was measured every hour from 7:00 a.m. to 6:00 p.m. Measurements were made twice a month from June to October 2001. Light measurement started immediately, 2 weeks after the cotton plants emerged. The two Ceptometers were used simultaneously to measure Q_i in external Rows (Row 1 and 16), the intermediate rows (Rows 4 and 13), and then the middle row (Row 8) to ensure minimal variation in light readings among the rows for the specific time of measurement. Ten random sample light readings along each row were recorded and averaged in each plot. Incoming radiation outside the orchard was also measured 1 m above the ground before and after measuring Q_i for each row.

An inverted Decagon Ceptometer located 1.0 m above the cotton also measured canopy reflected radiation. Reflected radiation in each row at the time of measurement was taken and then averaged. Light transmittance and reflection were measured on clear sunny days.

The transmission coefficient, *k*, for cotton growing in rows 1, 4, 8, 13, and 16 was calculated based on the Beer-Lambert law. Absorbed PAR by the cotton canopy in each row of both alleys was then determined from the calculated *k*, reflected PAR, and calculated LAI values:

$$\mathrm{APAR} = (\mathrm{Qi\text{- } reflected\ PAR}) \times (1 - \mathrm{Exp}\ (-\mathrm{k}^{*}\ \mathrm{LAI}) \qquad (6.2)$$

Litterfall was collected using 1 m × 0.5 m 2 mm screen litter traps. Four litter traps were randomly placed in each plot, of which one litter trap was installed per row. Litter traps were also installed under pecan trees to collect pecan foliage. Litter was collected twice a month from August to November 2002.

Leaves collected from litter traps were separated by species (pecan and cotton) and were stored, oven-dried at a constant temperature (70 °C), and then weighed. The litterfall and specific leaf area (SLA; leaf area per unit weight; described below) data were used to calculate the LAI of cotton plants in each row.

SLA of cotton was determined monthly in 2001 and 2002 by collecting six fully expanded leaves in each row. SLA of pecan was determined by harvesting 20 leaves each of sun and shade in August 2001 and August 2002, during the peak of pecan growth. Twenty-four pecan trees in the orchard and three trees in the monoculture pecan were sampled for SLA. Leaf area was determined using a leaf area meter (Li-Cor, Lincoln Nebraska), oven-dried for 3 days at 70 °C and weighed.

RUE (g MJ^{-1}) of cotton was determined for 2001 and 2002. Daily absorbed PAR by cotton, measured twice a month, was determined based on the diurnal (7:00 a.m. to 6:00 p.m.) readings of PAR.

Biomass and Lint Yield

In 2001, aboveground biomass of cotton was harvested at physiological maturity. In 2002, aboveground biomass was quantified monthly, from July to October. Whole plants (separated into leaves, stem, and bolls) were harvested in 1 m × 1 m subplots in each row in each plot. Harvested plants were dried for 72 h at 70 °C, and weighed. Biomass was expressed on a per area (m^2) basis.

Lint yield of cotton in each row (rows 1, 4, 8, 9, 13, and 16) in each treatment as well as in the sole stand (monoculture) was quantified by harvesting two random strips of 0.61 m × 6.1 m in each row. Lint dry weight was determined following oven drying (70 °C) for 48 h.

Data Analysis

Statistical analyses were performed using the proc-mixed procedure within the framework of Split block design (SAS Institute, Cary, NC). The Shapiro-Wilk's test was used to test for normality of distribution. A logarithmic (log(x + 1)) transformation was performed to improve normality when necessary. Least square mean differences were performed to determine significant differences of the means at $\alpha = 0.05$.

Results

Incident and Absorbed PAR

Light availability inside the pecan alley was affected by the LAI of pecan, which varied by treatment. Mean LAI of pecan in the barrier treatment (3.64) was 17% lower than that in the non-barrier treatment (4.39) (Table 6.1), resulting in 25% higher average growing season daily incident light transmittance for the barrier cotton plants (Figures 6.1 and 6.2). In general, the pecan trees caused about 50% reduction of incoming incident light to cotton plants compared to the daily average light received by the monoculture plants.

Table 6.1 Leaf area index (LAI), light extinction coefficient (k) and mean absorbed photosynthetically active radiation (PAR) of cotton in non-barrier, barrier, and monoculture treatments

Treatment	LAI Cotton	LAI Pecan	k	APAR (µmol m^{-2} S^{-1})
Non-barrier	1.72	4.39	0.51	541.44
Barrier	3.15	3.64	0.89	765.00
Monoculture	2.67	–	0.73	1330.65

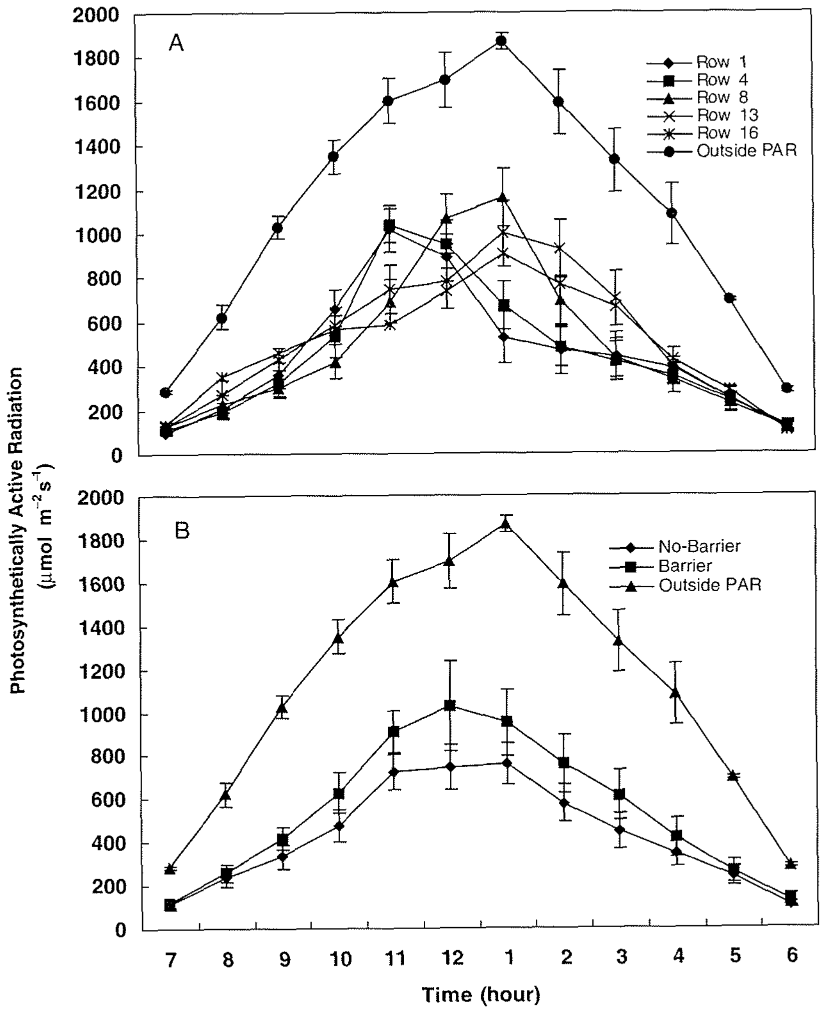

Figure 6.1 Average diurnal variation of light transmittance to cotton (A) in different rows and (B) in different treatments in a pecan-cotton alley-cropping system in northwest Florida

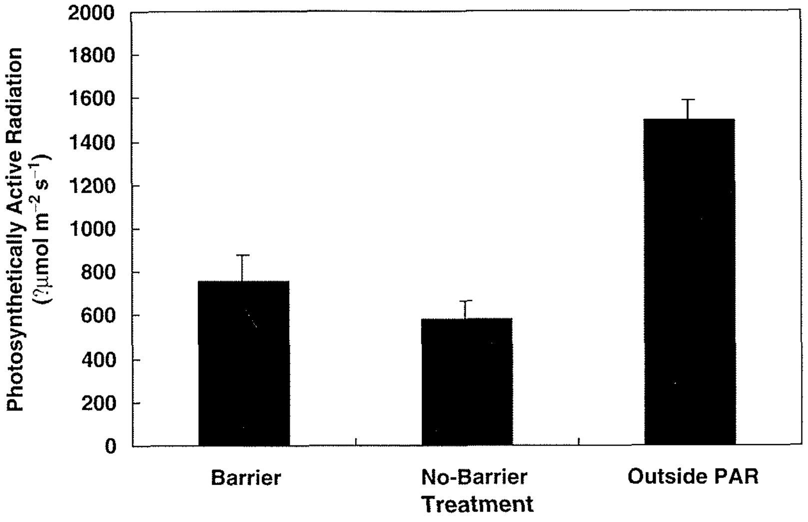

Figure 6.2 Mean photosynthetically active radiation transmitted to cotton in barrier, non-barrier and monoculture treatments in a pecan-cotton alley-cropping system in northwest Florida

Diurnal changes in spatial variation (resulting from row location) of incident PAR is illustrated in Figure 6.1a. Irrespective of the barrier treatment, incident light transmittance by row changed with time of the day, with rows situated on the eastern part of the alley (Rows 16 and 13) receiving more light during the morning hours while rows located on the western side (Rows 1 and 4) were shaded. However, this pattern was reversed in the afternoon, with eastern rows being shaded and western rows receiving greater amount of PAR. At midday, incident PAR was high in Row 8 (middle row) and remained high until mid-afternoon while all other rows also received high levels of PAR (Figure 6.1a).

LAI of cotton differed significantly among treatments. Cotton LAI values ranged from 1.72 for the non-barrier treatment to 3.15 for the barrier treatment. Lower LAI in non-barrier plants resulted in less light absorption. Differences in light extinction coefficients and absorbed PAR were also noted among treatments (Table 6.1). Cotton in the barrier treatment had greater amount of light absorbed and higher light attenuation compared to the non-barrier plants. The mean light extinction coefficient in monoculture plants was 17.9% lower than in barrier plants, but 30.1% higher than that in the non-barrier plants (Table 6.1). Although LAI of monoculture cotton was 15.2% lower than that of the barrier treatment, monoculture cotton exhibited greater light absorption due to higher incident PAR.

Light extinction coefficient showed a significant, but weak negative correlation with LAI ($R^2=0.43$) (Figure 6.3). PAR absorbed by cotton also exhibited significant curvilinear relationships with LAI ($R^2=0.61$ and $R^2=0.78$ for cotton growing in the orchard and in monoculture, respectively) (Figure 6.4).

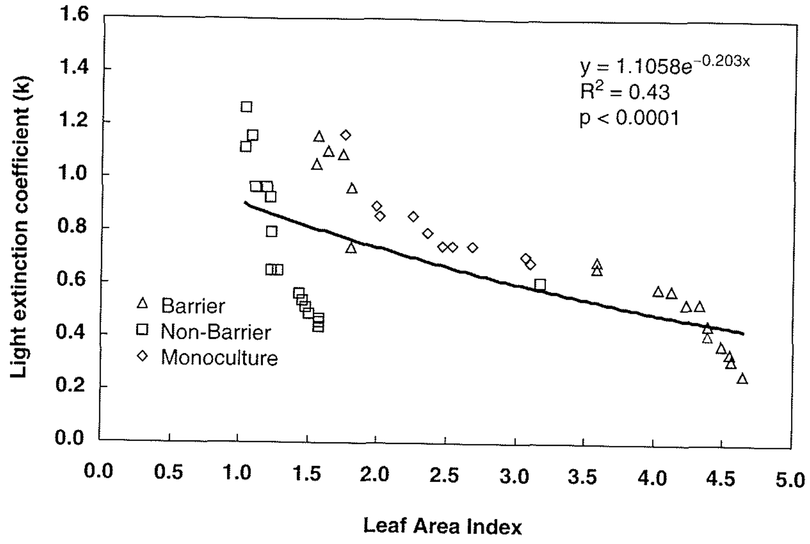

Figure 6.3 Relationship between LAI and light extinction coefficient (k) in a pecan-cotton alley-cropping system in northwest Florida

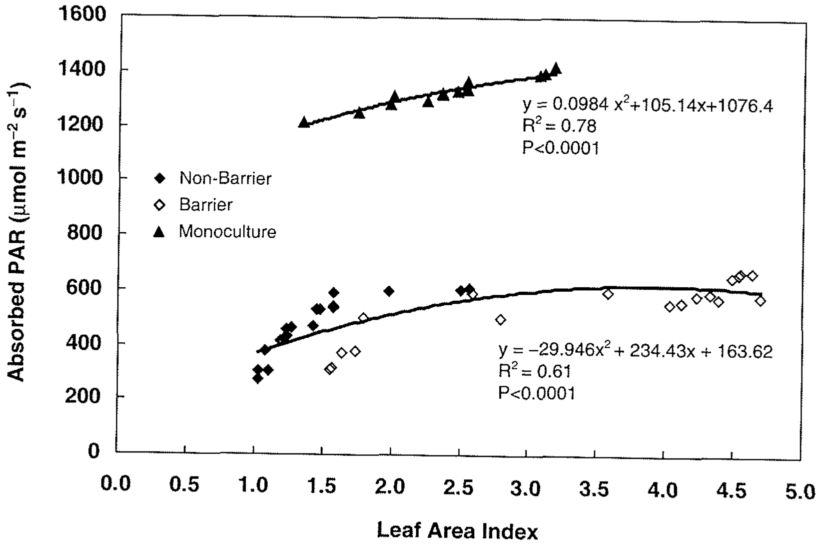

Figure 6.4 Relationship between LAI and absorbed photosynthetically active radiation in a pecan-cotton alley-cropping system in northwest Florida

Biomass and Lint Yield

Cotton in the barrier treatment produced 60% higher biomass compared to non-barrier treatment, but was statistically similar to biomass produced in monoculture both years of the study (Table 6.2). In 2002, there was an average 45% decline in aboveground dry matter across all treatments. Biomass in non-barrier treatment was 39.5% and 36.2% lower than that in the barrier and monoculture treatments, respectively.

In 2001, inter-row difference in aboveground biomass was significant ($P = 0.0038$) in the non-barrier treatment. Aboveground biomass increased in Row 8 ($P = 0.0014$) by 39% over Row 1 and by 15% compared to Row 4 ($P = 0.0091$). Inter-row variation in 2002 was not significant in either the barrier or the non-barrier treatments (Table 6.2).

Table 6.2 Aboveground biomass production of cotton in barrier, non-barrier, and monoculture treatments in 2001 and 2002 growing seasons

		Aboveground biomass (kg ha^{-1})		
Treatment	Row	Year 2001	Year 2002	% change
No barrier	1	284.17bc[a]	194.65a	32
		(31.22)[b]	(34.61)	
	4	336.27b	201.11a	40
		(34.38)	(34.06)	
	8	468.27a	192.17a	59
		(37.92)	(23.78)	
	Mean[c]	**362.91B**	**195.98B**	**46**
		(27.71)	(17.47)	
	p value[e]	0.0038	0.9403	
Barrier	1	526.09a	294.35a	44
		(70.91)	(30.70)	
	4	576.53a	292.54a	49
		(44.99)	(49.27)	
	8	622.45a	396.44a	36
		(56.10)	(73.08)	
	Mean[c]	**575.02A**	**323.74A**	**44**
		(32.89)	(30.02)	
	p value[e]	0.3021	0.1825	
Monoculture	**Mean**[c]	**545.82A**	**307.09A**	**44**
		(21.23)	(11.81)	
p value[d]		0.0020	0.0303	

[a] Within-treatment values followed by the same lowercase letter are not significantly different at the 0.05 level of probability.
[b] Standard error of the mean are given in parenthesis.
[c] Teatment means.
[d] *p* value indicated significance between treatment means.
[e] *p* value indicated significance among rows in specific treatment.

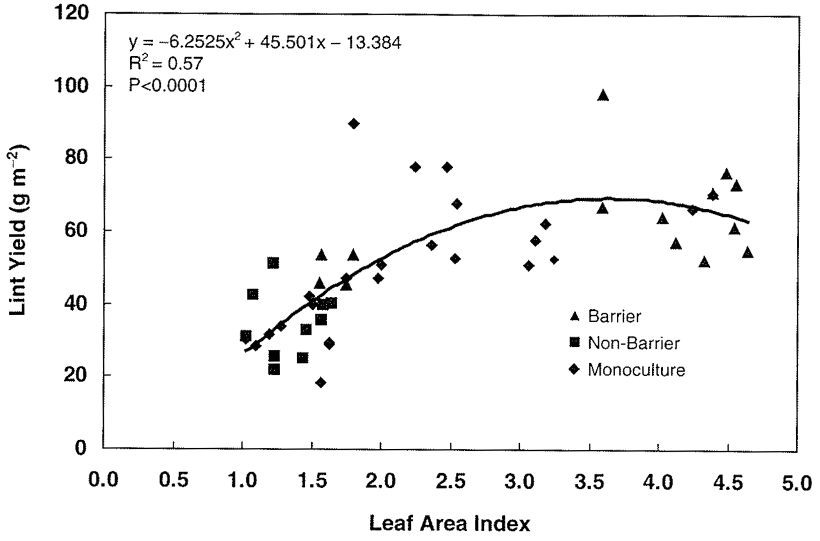

Figure 6.5 Relationship between LAI and cotton lint yield in a pecan-cotton alley-cropping system in northwest Florida

Restricting belowground competition had an impact on cotton lint yield both years and lint yield differed significantly between 2001 and 2002. In 2001, lint yield in the barrier treatment (70.04 g m^{-2}) was higher than that of the non-barrier treatment (51.54 g m^{-2}) ($P = 0.0324$), but was not different from the monoculture treatment (69.01 g m^{-2}). In 2002, lint yield in barrier treatment was again higher than the non-barrier treatment but lower than monoculture. Inter-row variation in lint yield was not significant for the non-barrier treatment. However, the presence of the barrier had the greatest impact on plants in row 1 resulting in greater yield compared to the intermediate and middle rows.

LAI and lint yield showed a significant curvilinear relationship in our experiment ($R^2 = 0.45$; $P < 0.0001$) (Figure 6.5). Maximum lint yield was obtained when LAI was between 3.0 and 4.0. Increase in LAI beyond 4.0 did not result in an increase in lint yield.

Radiation-Use Efficiency

Cotton aboveground biomass and lint yield were both influenced by levels of cumulative absorbed PAR. Although R^2 values ($R^2 = 0.44$ and $R^2 = 0.41$, respectively for 2001 and 2002) were low, the relationship between aboveground biomass and PAR was significant and linear (Figure 6.6). Similarly, lint yield of cotton exhibited significant and strong curvilinear relationship with cumulative absorbed PAR ($R^2 = 0.61$, $R^2 = 0.58$) (Figure 6.7). Apparently, maximum lint yield (90 g m^{-2} for

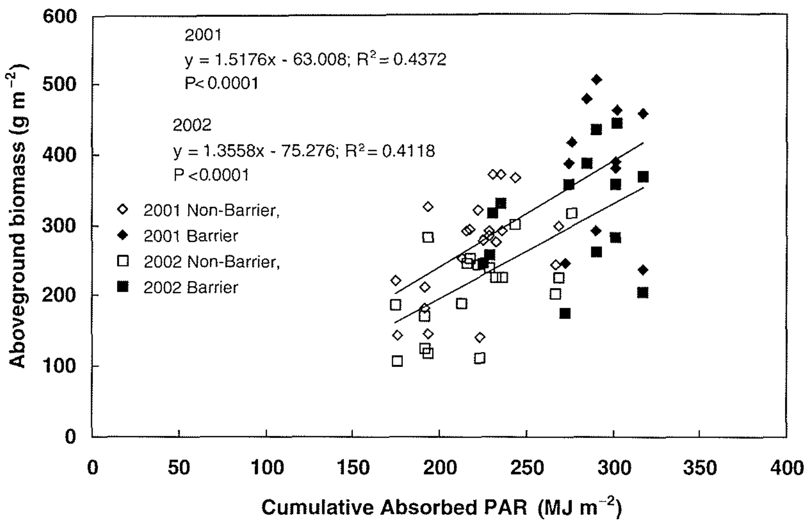

Figure 6.6 Relationship between aboveground biomass production and cumulative absorbed PAR in a pecan-cotton alley-cropping system in northwest Florida

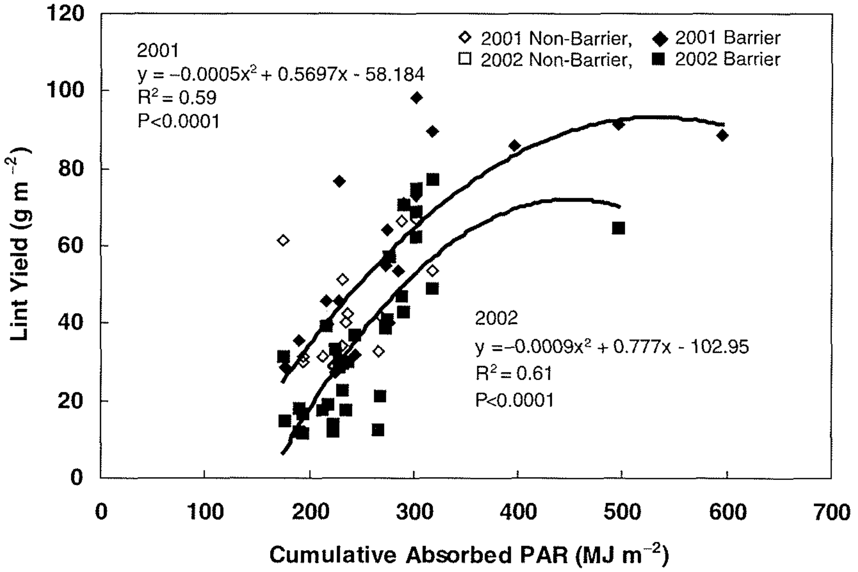

Figure 6.7 Relationship between lint yield production and cumulative absorbed PAR in a pecan-cotton alley-cropping system in northwestern Florida

barrier treatment and 70 g m^{-2} for non-barrier) was achieved at approximately 500 MJ m^{-2} and 400 MJ m^{-2}, respectively, for the barrier and non-barrier treatments (Figure 6.7).

Significantly higher leaf area of the barrier plants that captured more light resulted in 31% and 52% higher RUE than that in the non-barrier and monoculture plants (Table 6.3). RUE in 2001 did differ significantly among treatments ($P = 0.0017$). However, there was an average 47% reduction in RUE in all treatments in 2002 compared to 2001 (Table 6.3). Monoculture plants had the lowest RUE in both years and were statistically similar to that of the non-barrier plants in 2002. Inter-row variation in RUE was nonsignificant both years in all the treatments except for non-barrier plants in 2001. In the non-barrier treatment, RUE of plants in Row 1 was significantly lower than that in rows 4 and 8 ($P = 0.0002$) (Table 6.3).

Table 6.3 Radiation use efficiency of cotton in barrier, non-barrier, and monoculture treatments in 2001 and 2002 growing seasons

		Radiation use efficiency (g MJ^{-1})		
		Year		
Treatment	Row	2001	2002	% change
No barrier	1	1.07c[a]	0.71a	34
		(0.16)[b]	(0.20)	
	4	1.53b	0.92a	40
		(0.09)	(0.12)	
	8	2.13a	0.9a	58
		(0.13)	(0.14)	
	Mean[c]	**1.57B**	**0.84B**	**46**
		(0.19)	(0.12)	
	p value[e]	0.0002	0.4115	
Barrier	1	1.99a	1.09a	45
		(0.22)	(0.10)	
	4	2.41a	1.11a	54
		(0.40)	(0.14)	
	8	2.37a	1.38a	42
		(0.27)	(0.20)	
	Mean[c]	**2.26A**	**1.19A**	**47**
		(0.20)	(0.12)	
	p value[e]	0.3201	0.1928	
Monoculture	**Mean**[c]	**1.09C**	**0.58B**	**49**
		(0.04)	(0.02)	
p value[d]		0.0017	0.0031	

[a] Within-treatment values followed by the same lowercase letter are not significantly different at the 0.05 level of probability.

[b] standard error of the mean are given in parenthesis.

[c] Treatment means.

[d] *p* value indicated significance between treatment means.

[e] *p* value indicated significance among rows in specific treatment.

Discussion

Light has been identified as one of the major limiting factors influencing production in many agroforestry systems (Monteith et al. 1991; Corlette et al. 1992; Nair, 1993; Chirko et al. 1996; Jose et al. 2004) including temperate (Gordon et al. 1997; Gillespie et al. 2000) and tropical (Lawson and Kang, 1990; Karim et al. 1993; Nissen et al. 1999) alley cropping. In all these studies, decrease in incident light resulted in lower crop production.

In our study, aboveground biomass and yield of cotton were strongly affected by the amount of light absorbed by cotton. The amount of light absorbed, in turn, was a function of both the amount of incident light and cotton leaf area. Although the absorbed PAR was 42% lower for the barrier plants compared to the monoculture plants in 2001 (Table 6.1), lint yield was similar for both treatments. This clearly supports our hypothesis that cotton can grow and yield reasonably well under moderate shade (50% shade in the barrier compared to monoculture, Figure 6.2). However, as hypothesized, if belowground competition for water and nutrients existed (as in the non-barrier treatment), PAR capture was lower because of reduction in cotton LAI, hence resulting in lower yield. LAI of plants in the non-barrier treatment was 45% lower than in the barrier treatment. Barrier plants outperformed non-barrier plants in both years with nearly 40% and 60% higher biomass and yield. Lower pecan leaf production and self-shedding that took place in both years (personal observation) also resulted in slightly higher transmission of incident light to the barrier plants compared to the non-barrier plants.

LAI has long been recognized as an indicator of plant productivity. Although, regression analysis showed a weak relationship between LAI and yield in our experiment ($R^2 = 0.45$), the relationship was still significant ($P < 0.0001$) (Figure 6.5). Rosenthal and Gerik (1991) reported a similar, but stronger relationship ($R^2 = 0.90$) between absorbed PAR and lint yield for cotton grown under irrigated conditions. Cotton plants in our system attained maximum yield (approximately 65 g m^{-2}) between LAI values of 3.0 and 4.0, which is in agreement with Heitholt et al. (1992) who observed maximum yield between the same range of LAI. Heitholt et al. (1992) further concluded that this range of LAI provided the optimum absorption of incident light by cotton, which is also in agreement with our results (Figure 6.4).

The trade-off hypothesis (Smith and Huston, 1989) states that plants grown under shade tend to preferentially allocate carbon in building larger canopies, for greater capture of light, at the expense of root systems (Kozlowski and Pallardy, 1997; Jose et al. 2002). Despite shading, there was no such increase in leaf area in the non-barrier treatment compared to the monoculture treatment. However, eliminating belowground competition resulted in larger canopy (higher aboveground biomass, Zamora et al. 2006, 2007) and higher LAI for the barrier plants in response to shading. Similar results have been reported before. For example, Zhao and Oosterhius (1998) noted in their experiment that cotton under shade expanded their leaves resulting in larger leaves and higher LAI. Increasing leaf area by the plants enhances the ability to capture more light under light limiting conditions. As expected, distance from tree rows had an impact on the growth of non-barrier plants, affecting their biomass and yield. For the non-barrier plants, any benefit from the edge effect (increased development due to lack of intraspecific competition on one side) was not detected. Instead, there was a trend of decreasing LAI and yield with closer proximity to the tree row. This reaffirms the earlier findings from the same study site that competition for water is perhaps intense in the non-barrier treatment compared to the barrier treatment (Wanvestraut et al. 2004).

RUE is an indirect expression of the photosynthetic capacity of plants at the whole plant level (Muchow and Sinclair, 1993; Bennett et al. 1993). The barrier plants had 30% higher efficiency in utilizing light and converting it into biomass in both years compared to the non-barrier plants. In 2002, RUE in non-barrier plants was statistically similar to that of monoculture plants. Lower light interception, coupled with competition for belowground resources in the non-barrier treatment, affected biomass production and consequently RUE by the non-barrier plants (Table 6.3). With high levels of light available for growth, monoculture plants exhibited about 50% lower RUE compared to the barrier plants. The values we observed for RUE (0.71–2.37 g MJ^{-1}) are within the range of published values for C_3plants. Kiniry et al. (1989) found RUE ranging from 2.0 g MJ^{-1} to 3.0 g MJ^{-1} while Rosenthal and Gerik (1991) found RUE values of 1.3–1.5 g MJ^{-1} for cotton grown in a narrow-row planting configuration.

In addition to light, competition for water and nutrients can also affect RUE through their effect on plant growth. For example, Bange and Milroy (1998) showed that cotton fertilized with 150 kg ha^{-1} of N had higher RUE (1.07 g MJ^{-1}) than cotton receiving only 113 kg ha^{-1} N (0.89 g MJ^{-}1). Sinclair and Horie (1989) found that foliar nitrogen was positively correlated to RUE of cotton grown under open field conditions. The decline in RUE from 2001 to 2002 in our system could also be attributed to decline in soil nutrient status. Allen (2003) reported a significant decrease in soil nitrogen mineralization rate in our system from 2001 to 2002 growing season, which was caused by a declining fallow effect.

Conclusions

Despite having lower light transmittance (about 50% of outside PAR) in the alleys, cotton aboveground biomass was comparable to monoculture in both years. It is reasonable to assume that light is not a limiting factor in the production of cotton in our alley-cropping system. Cotton tolerated moderate shade and provided acceptable yield when belowground competition was alleviated. Results also revealed a curvilinear relationship between light absorbance and lint yield. Light absorbance, in turn, was influenced by LAI, which varied significantly among treatments. The optimum LAI (3.0–4.0) for maximum light absorbance and lint yield was observed in both the monoculture and the barrier treatments, indicating that competition for belowground resources played a major role than competition for light in this particular system. The results offer promise for establishing alley-cropping systems in new or existing nut or fruit orchards by planting C_3 crops in the alleys. However, management strategies such as early root training or root pruning need to be explored so that belowground competition for resources could be alleviated.

Acknowledgments We wish to thank Sara Merrit, Cathy Hardin, Doug Hatfield and Joe Nelson for assistance in field and laboratory studies. This research was funded in part by two grants; one from the USDA Southern Region Sustainable Agriculture Research and Education (SARE) program (# LS02–136) and the Center for Subtropical Agroforestry (CSTAF) at the University of Florida through a USDA-CSREES grant # 00–52103–9702. Florida Agricultural Experiment Station Journal Series No. R-10928.

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Chapter 7

Modification of Microclimate and Associated Food Crop Productivity in an Alley-cropping System in Northern Sudan

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Introduction

The northern region of Sudan consists of desert and semidesert prone to low rainfall, poor agricultural productivity and desertification, resulting in a continual decline in the area of cultivated land. The prevailing harsh conditions in the region (high solar radiation and temperature and low relative humidity), particularly during the summer season, prevent cropping during this period. This situation necessitates the development of intensive plantations of woody trees, which could provide a variety of economic and environmental benefits for farmers and communities. However, the high cost of irrigation water and a lack of short-term returns to the farmer until the trees become economically valuable are obstacles to the development of afforestation programs in the area. On the other hand, agroforestry, which integrates crops and/or livestock with trees and shrubs, has a great potential in the area as it could provide farmers with multiple benefits, including diversified income sources, increased biological production and better water quality.

Agroforestry systems such as intercropping offer substantial scope for complementarity of water use since the root system of woody trees is much deeper than those of agricultural crops. While crops intensively utilize water from shallow depths in the soil profile, trees have the potential to extract water from deeper soil layers (Narain et al. 1998).

In agroforestry systems, the tree canopy reduces and modifies light availability to plants in the understory, changing photosynthetic and hydrological regimes, with possible consequences for understory plant morphogenesis (Bergez et al. 1997). Several studies have shown the beneficial effects of trees on associated crops in agroforestry systems. For example, Yu et al. (1997) reported that *Paulownia* trees modified the microclimate and favored the growth of tea (*Camellia sinesis*) plants, improving the quality of tea leaves. This, in turn, increased economic returns per unit land area. However, the complexity of climatic interactions makes interpretation of

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

these interactions difficult in most systems (Hawke and Wedderburn, 1994). Lack of information on environmental interactions between trees and crops requires investigations into the nature of competitive and complementary relationships among and between system components. The objective of this study was to determine the effects of microclimatic modifications attributed to alley cropping on the productivity of three winter crops (*Triticum aestivum, Vicia faba*, and *Phaseolus vulgaris*), two summer crops (*Daucus carota* and *Capsicum annum*) and one autumn crop (*Sorghum bicolor*).

Methodology

Experimental Site

An alley cropping experimental area was established in 1998–2000 at Hudieba Research Station (HRS), 300 km north of Khartoum, Sudan (17.57′N and 33.8′E). The soil of the site belongs to Aridisols – Typic Calciorthids – (Soil Survey Staff, 1975). The percentage of $CaCO_3$ ranges from 17 to 38 and increases with depth. It is characterized by very low organic carbon (0.03–0.09%) and decreases with depth. Soil texture is loamy sand in the top 30 cm and clay content increases with depth. The study area lies within desert to semidesert with annual rainfall ranging between 0 and 150 mm. The summer season is characterized by low humidity (22%) and high temperatures (40 °C). Winds are usually from the north or northeast.

Experimental Layout

Three-month-old *Acacia stenophylla* seedlings were planted at 3 m intra-row spacing and 6.3 m inter-row spacing in each hedge row which was 90 m long and arranged in an east–west direction. Each hedgerow comprised 30 trees. The alley-cropping study was conducted during 1999 and 2000 cropping seasons. *A. stenophylla* trees were 36-months-old and had an average height of 4.3 m, diameter at breast height (DBH) of 3.5 cm and diameter at the base of 5.7 cm, at the beginning of the experiment. The alley was divided into three zones: northern, central, and southern. The central zone had the largest width (4 m), while the northern and the southern zones were each 1.0 m wide. Weather stations were mounted in each of the three zones of the alley and in the control plot for monitoring maximum, minimum temperatures, and relative humidity. Cup anemometers were installed in the central part of alley and in the control plot for measuring wind speed.

During seasons 1999 and 2000, winter, summer, and autumn crops were grown in the alleys (details given below). Each crop was assigned randomly in a randomized complete block design replicated three times. The plot size was 3 × 6 m. Similar sole crops were planted on the eastern side of the alley-cropping plots, as control, to avoid both shading and the sheltering effects from the predominant north-easterly winds. The crops included:

Winter crops: The seeds of wheat (*Triticum aestivum*, variety Wadi El Neil), faba bean (*Vicia faba*, variety Hudieba 72), and common bean (*Phaseolus vulgaris*, variety Basabeer) were sown in mid-November 2000. Watering was applied at intervals of 7–10 days. Harvesting was at 110–120 days from seed sowing.

Summer crops: The seeds of carrot (*Daucus carota*, variety Chantenay Red Cored) and sweet pepper (*Capsicum annum*, variety California Wonder) were sown on 27 January 2000. The crop was kept as far as possible free from weeds and pests. Irrigation was applied at 5- to 7-day interval.

Autumn crops: Seeds of the sorghum (*Sorghum bicolor*, variety Abu 70) were sown in early July in the two consecutive seasons of 1999 and 2000. The plants were irrigated at weekly intervals.

Data Collection

Crop Data

Plant samples of wheat, faba bean, and common bean were taken at harvest from an area of 1 m^2 in the center of the northern, southern, and central zones and control plots. Harvesting of sweet pepper started 3 months after seed sowing and fruits were picked every 15–25 days. For carrot, roots were harvested 4 months from seed sowing. Harvesting of sorghum was done at the beginning of October.

Meteorological Data

Stevenson screens were mounted on iron stands about 2.0 m aboveground. One screen was placed in each zone of the alley and control plot. Thermometers were used for reading maximum and minimum temperatures, while wet- and dry-bulb thermometers were used for determining humidity. The readings of all thermometers were taken simultaneously at 08:00 a.m.

Tube solarimeters (Delta-T TSL, 85.8 × 2.2 cm, sensitive to solar radiation of 0.35–2.5 μm) coupled with microvolt integrators (Delta-T) were placed at ground level across the three zones of the alley and the control plot. Measurements from each of three replicate were taken three times a day (09:00 a.m., 12:00 a.m., and 4:00 p.m.) at 10-day intervals.

Anemometers were located in the central part of the alleys and control plots at 2.0 m aboveground. Observations were taken every day, at 08:00 a.m., 1:00 and 08:00 p.m. Wind speed in the alleys was calculated as a ratio of that in the control.

Measurement of Applied Irrigation Water and Soil Moisture

During each cropping season, measurement of applied irrigation water was carried out using a water meter (in cubic meters) both in alley cropping and control plots. Soil moisture was measured using gravimetric sampling for the depths of 15, 30, 45, and 60 cm, after irrigation and immediately before subsequent irrigation. Soil samples were dried at 105 °C for 24 h and gravimetric soil water content was calculated on a dry weight basis. Soil water depletion was calculated as the difference between applied water and water remaining in the soil for each irrigation cycle. Reference evapotranspiration (ET_0) was estimated by Penman Monteith Formula, using the computer program CROPWAT (version 5.7, 1992).

Statistical Analysis

Water use, moisture content, yield, and yield components data were statistically analyzed using analysis of variance within the frame work of a randomized complete block design (MSTAT Package).

Results and Discussion

Microclimatic Modification

Tables 7.1, 7.2, and 7.3 demonstrate that during the winter season of 2000 the solar irradiance in the control was 0.284 kw m^{-2} the maximum and minimum temperatures were 32.6 °C and 17.3 °C, respectively. Relative humidity was 42%; while the wind speed was 2.8 m s^{-1}. Due to the modifications of microclimate during this season, solar irradiance in alley cropping was only 63% of control (this equals a reduction of 37% in solar irradiance in alley cropping). While the maximum and minimum temperatures were reduced by 1.4 °C and 0.7 °C, respectively, the relative humidity was increased by 8%. The wind speed was 66% of the control.

Summer growing season, among the other seasons, had the highest average of solar irradiance (0.395 kw m^{-2}), maximum and minimum temperatures (40.3 °C and 24.3 °C, respectively), and lowest average relative humidity (24%). The average wind speed during this season was 2.9 m s^{-1} (Tables 7.1, 7.2, and 7.3). During this season, the modifications in microclimate resulted in an average reduction in solar irradiance and in both maximum and minimum temperatures by 36% and 1.7 °C, respectively. The wind speed was 57% of that in the control, while the relative humidity was increased by 13%.

The autumn season had moderate solar irradiance (0.336 kw m^{-2}), maximum and minimum temperatures were 39.5 °C and 28 °C, respectively. However, the season

Table 7.1 Average variation in maximum and minimum temperatures and relative humidity in the different zones of the alleys as differences from the control plot during 1998–2000 at Hudieba Research Station experimental site in Northern Sudan

	Control			Southern zone			Central zone			Northern zone			Average in the alley		
Seasons*	Max(°C)	Min(°C)	R.H(%)	Max(°C)	Min(°C)	R.H(%)	Max(°C)	Min(°C)	R.H(%)	Max(°C)	Min(°C)	R.H(%)	Max(°C)	Min(°C)	R.H(%)
Winter 98	30.6	12.9	40	−1.3	−0.5	11+	−1.3	−0.5	11+	−1.3	−0.5	11+	−1.3	−0.5	+11
Summer 98	40.0	23.4	20	−1.3	−1.4	16+	−1.3	−1.4	16+	−1.3	−1.4	16+	−1.3	−1.4	+16
Autumn 98	39.8	27.6	48	−1.8	−1.4	10+	−1.0	−0.9	7+	−1.4	−1.3	10+	−1	−0.9	+7
Winter 99	33.6	18.1	48	−2.3	−1.0	10+	−0.8	−0.6	8+	−1.1	−0.4	8+	−0.8	−0.6	+8
Summer 99	41.0	24.2	23	−1.6	−1.5	15+	−1.6	−1.4	14+	−2.0	−1.8	16+	−1.6	−1.4	+14
Autumn 99	39.8	27.3	47	−1.7	−1.1	11+	−1.3	−0.6	9+	−1.5	−1.1	12+	−1.3	−0.6	+9
Winter 2000	32.6	17.3	42	−2.0	−1.0	9+	−1.1	−0.7	6+	−1.1	−0.4	7+	−1.1	−0.7	+6
Summer 2000	40.3	24.3	24	−1.6	−1.6	15+	−1.7	−1.7	13+	−1.9	−1.6	17+	−1.7	−1.7	+13
Autumn 2000	39.5	28.0	41	−1.6	−1.3	11+	−1.4	−1.1	9+	−1.4	−1.2	12	−1.4	−1.1	+9

*Season: Average of four months of each season

–Elements in zones are lower than control

+ Elements in zones are higher than control

Table 7.2 Average wind speed in alleys, control plots, and the ratio of alley to control during 1998–2000 at Hudieba Research Station experimental site in Northern Sudan

	Mean 12 h			Mean of 24 h		
Seasons	Control (m s^{-1})	Alley (m s^{-1})	Alley/co (%)	Control (m s^{-1})	Alley (m s^{-1})	Alley/co (%)
Winter 98	3.2	–	–	2.8	–	–
Summer 98	3.4	1.8	53	2.9	1.3	45
Autumn 98	3.2	2.1	66	2.8	1.7	61
Winter 99	3.0	2.0	67	2.5	1.5	60
Summer 99	3.3	1.8	55	3.0	1.5	50
Autumn 99	3.0	2.0	67	2.6	1.6	63
Winter 2000	3.1	2.2	71	2.8	1.9	68
Summer2000	3.4	2.1	62	2.9	1.7	59
Autumn 2000	3.2	2.2	69	2.7	1.7	63

Table 7.3 Irradiance in various zones of the alley as values and as a percentage of control during 1998–2000 at Hudieba Research Station experimental site in Northern Sudan

	Control	Southern zone		Central zone		Northern zone		Average in the alley		
Seasons	kw m^{-2}	kw m^{-2}	S/co	kw m^{-2}	C/co	kw m^{-2}	N/co	kw m^{-2}	*X*/co	Reduction
Winter 98	0.317	0.165	52	0.285	90	0.295	93	0.247	78	22%
Summer 98	0.396	0.341	86	0.384	97	0.222	56	0.313	79	21%
Autumn 98	0.34	0.228	67	0.299	88	0.187	55	0.235	69	31%
Winter 99	0.287	0.126	44	0.227	79	0.221	77	0.189	66	34%
Summer 99	0.397	0.266	67	0.318	80	0.210	53	0.262	66	34%
Autumn 99	0.34	0.190	56	0.255	75	0.177	52	0.207	61	39%
Winter 2000	0.284	0.119	42	0.210	74	0.213	75	0.179	63	37%
Summer 2000	0.395	0.253	64	0.304	77	0.198	50	0.253	64	36%
Autumn 2000	0.336	0.175	52	0.232	69	0.168	50	0.192	57	43%

S/co: southern zone/control
C/co: central zone/control
N/co: northern zone/control

was characterized by high relative humidity (41%) and high wind speed (2.7 m s^{-1}). Microclimatic modifications were manifested in reduction in solar irradiance by 43%, and maximum and minimum temperatures by 1.4 °C and 1.1 °C, respectively, compared to the control. Relative humidity was increased by 9%, while wind speed was 57% of the control.

Water Use

Table 7.4 Moisture content within different depths in the alleycropping and control during the season of 1999–2000 at Hudieba Research Station experimental site in Northern Sudan

Seasons treatments		Depths treatments		Alleycropping and control	
Seasons	Moisture content mm m^{-1}	Depths (cm)	Moisture content mm m^{-1}	Locations	Moisture content mm m^{-1}
Winter	8.1	15	2.1	Control	7.0
Summer	8.5	30	4.5	Alley	8.7
Autumn	6.8	45	8.6	–	–
–		60	16.3	–	–
Sig. level	***	***		***	
S.E±	0.094	0.10		0.07	
Interactions between different seasons and different sowing depths					
Seasons	Treatments	15 cm	30 cm	45 cm	60 cm
Winter	Control	1.5	2.6	6.7	17.8
	Alley cropping	2.6	5.8	10.7	17.9
Summer	Control	1.0	2.7	5.5	13.7
	Alley cropping	2.6	5.8	9.1	15.8
Autumn	Control	1.7	4.4	9.5	16.9
	Alley cropping	3.0	6.5	10.3	16.0
Sig. level			***		
S.E±			0.26		
C.V %			5.87		

*** $P = 0.0001$

Agroforestry combinations have potential in improving water use efficiency compared to monocropping systems. In this study, soil water content was much higher in alley-cropped plots than in the control, especially in the depths from 15 to 45 cm (Table 7.4). However, in the depth of 60 cm the values were almost similar in the alley cropping and control plots. Table 7.5 shows that alley cropping plots consumed less water than the control. This could be explained by the estimated Reference Evapotranspiration (ET_0). ET_0 in the central zone of the alley was only 70–74% of ET_0 in the control (Table 7.6). Ong and Leakey (1999) reported that agroforestry could improve exploitation of soil water, if species involved differ appreciably in their patterns or duration of rooting. *A.stenophylla* tree was investigated in alley-cropping system in the Northern Sudan to determine its ability for exploiting residual water in the surface horizons and beyond the rooting depth of associated crops. *A.stenophylla* tree, with its deep roots and open canopy, gave the highest saving in irrigation water (Shapo, 2006). These results confirmed the previous findings of Jiang et al. (1994), who observed that the root system of Paulownia trees was much deeper than those of wheat and maize. The former was mainly distributed in the soil below 40 cm, while the latter mostly remained in the upper soil layers (about 30–40 cm).

Behavior of Winter Crops

The winter season in the study area, is generally short and warm. The lowest temperatures occur at the time of wheat sowing (November) and the time of its maturity (March). Ishag (1995) reported that high temperature is one of the major constraints

Table 7.5 Water used in alleycropping system compared to control in different seasons at Hudieba Research Station experimental site in Northern Sudan

	Water m^3ha^{-1}		
Cropping season	Control	Alley area	%Water saved
Average winter crops	980	714	27%
Significance level		***	
S.E±		10.5	
C.V%		8.3	
Average summer crops	1092	430	60%
Significance level		***	
S.E±		5.5	
C.V%		5.4	
Average autumn crops	1054	809	23%
Significance level		**	
S.E±		24	
C.V%		17.9	

**$P = 0.001$; ***$P = 0.0001$.

Table 7.6 Reference Evapotranspiration (ET_0) in alleys and control plots and the ratio of alley to control at Hudieba Research Station experimental site in Northern Sudan

	Evapotranspiration (ET_0) (mm day^{-1}) 1999			Evapotranspiration (ET_0) (mm day^{-1}) 2000		
Season	Control	Alley	Alley/ control (%)	Control	Alley	Alley/ control (%)
Winter	5.9	4.3	73	6.0	4.5	75
Summer	9.1	6.4	70	9.0	6.3	70
Autumn	7.4	5.5	74	7.8	5.8	74

for wheat production in the Sudan as it hastened developmental phases (heading and maturity). He also reported that when the tested cultivars (i.e. Wadi El Neil) were subjected to high temperatures they showed some of the undesirable characteristics, such as stunted plant growth, smaller head (low number of grains/head), smaller grain size, shriveling, and low grain yield.

During the winter season of the study area, the microclimatic modifications in the alley-cropping plots were significant. Solar irradiance differed greatly within the different zones of the alley. The southern zone of the alley, throughout the growing season, was permanently shaded. This zone had the highest increase in relative humidity and highest reduction in air temperatures; however, it had the lowest value of solar irradiance (Tables 7.2 and 7.3). Table 7.7 demonstrates that the three winter crops grown in this zone had significantly taller plants than those in the control plots, but had lower number of pods (common bean and faba bean) and spikes (wheat). Yields of the three crops were, therefore, reduced in this zone by 6.9%, 7%, and 20% for wheat, common bean, and faba bean, respectively. The faba bean plants were taller in this zone and tended to lodge, so their yields were drastically reduced.

In contrast, the northern zone of the alley was the one mostly exposed to sunlight during most of the growing season. In this zone, the three winter crops had the lowest plant height. The yield of wheat in this zone increased by 51%, while the yields of the other two crops were similar to their yields in the control plots (Table 7.7).

Table 7.7 Yield and yield components of wheat, faba bean and common bean crops in different zones of the alley and control plots at Hudieba Research Station experimental site during 1999–2000 in Northern Sudan

	Wheat crop			Faba bean crop			Common bean cop		
Treatments	Plant height (cm)	No. Spikes/ m^2	Grain yield (kg/ha)	Plant height (cm)	No. of pod (s/m^2)	Grain yield (kg/ha)	Plant height (cm)	No. pods/ plot	Grain yield (kg/ha)
Control	52	304	2456	63	204	1395	17	189	1228
Southern alley	71	208	2286	90	141	1108	29	153	1142
Central alley	82	259	4733	100	192	1908	25	196	1442
Northern alley	64	212	3723	75	144	1391	15	170	1199
Sig. level	***	***	***	**	***	***	**	**	*
SE±	1.5	6.3	49.9	3.2	6.3	33.9	1.2	2.3	49.9
C.V %	3.7	4.5	2.6	6.6	6.4	4.1	8.8	7.1	6.8

* $P = 0.01$; ** $P = 0.001$; *** $P = 0.0001$

The modifications in the central zone of the alley, with respect to solar irradiance and other microenvironmental factors were almost similar to that in the northern alley. However, solar irradiance differed greatly in its time of occurrence in each zone. The central zone of the alley experienced the longest shade and lowest solar irradiance during the first 2 months of the growing season, which coincided with the vegetative stage of the winter crops. While during the reproductive stage (January–March), the shade in this zone became shorter and had higher energy. Thereby, the crops benefited from the partial shade during the vegetative stage and from the higher energy during the reproductive stage (grain filling). Therefore, the highest crop yields were obtained in this zone. Compared to the control plots, the increases in crops yields in the central zone of the alley were 92%, 37%, and 17% for wheat, faba bean, and common bean, respectively (Table 7.7). The increase of yield in this zone had compensated the reduction caused by low radiation in the southern alley. Therefore, the average yield in the alley plots increased over control by 69%, 15%, and 10% for wheat, faba bean, and common bean, respectively. Schroth et al. (1995) reported that hedgerows at 5 m spacing between the rows increased groundnut yields in the alley by increasing pod numbers per plant. Alley cropping tended to increase pod yields, although crop yields at the tree-crop interface were depressed by 68% compared to the central parts of the alleys.

Within the evaluated crops, the variation in yield increase could be explained by variation in light-use efficiency. The high increase in yield of wheat could be attributed to its errectophilic nature of leaf arrangement allowing it to intercept most of the transmitted radiation. Within the planophilic grain legumes the relative yield advantage of faba been could be attributed to its growth habit exposing most of its leaf area to transmitted radiation. On the other hand, the prostrate growth habit of Common bean and its overlapping leaves reduced the area exposed to irradiance resulting in lower photosynthetic rate and thus relatively low yields. It was evident that wheat was a very promising crop for intercropping system. Zhaohua (1998) demonstrated that competition for light between wheat and *Paulownia* was not serious. Paulownia intercropping systems increased wheat yield by about 5–12% compared to the open fields by improving the microclimate (Ni, 1988).

Behavior of Summer Crop

The summer season was characterized by high wind speed and solar radiation, which increased evapotranspiration and caused water stress for the plants growing in the control plots (Tables 7.2 and 7.3). Thus, during the vegetative stage, shoot of the carrot crop was drastically stunted, while the sweet pepper plants died after 1 month from date of sowing (Tables 7.8 and 7.9).

The microclimatic modifications in the alley-cropping plots were significant as explained earlier. Consequently, carrot in the alley had an increase in yield of 487% over the control. The alley-cropped sweet pepper had a fruit yield of 5833 kg ha^{-1} compared to zero yield in the control.

The northern zone of the alley had the longest shade, highest reduction in solar energy, maximum, and minimum temperatures and maximum increase in relative humidity. Carrot yields were increased as solar radiation decreased. Thus, the highest carrot yield was obtained in the northern zone of the alley (Table 7.8). However, there were no differences in sweet pepper production in the different zones of the alley (Table 7.9). The absence of differences between the zones of the alley were most probably due to the relatively longer season of harvesting, since each zone had sufficient period of optimum solar energy.

Table 7.8 Carrot production in different zones of alleycropping and control plots at Hudieba Research Station experimental site in Northern Sudan

Treatments	No. plant/m	Stem fresh wt (g)	Fruit fresh wt (g)	Fruit dry wt (g)
Control	6	33	24	5
South	13	334	163	28
Centre	10	193	119	22
North	19	439	207	39
Sig. level	*	**	***	**
SE±	1.6	11.9	10.3	2.7
C.V %	10.1	7.85	7.94	9.45

*$P = 0.01$; **$P = 0.001$; ***$P = 0.0001$

Table 7.9 Sweet pepper production in different zones of alley-cropping and control plots at Hudieba Research Station experimental site in Northern Sudan

Treatments	No. fruit/m	Fruit dry (kg/ha)	Fruit fresh wt(g)
South	79	350	1600
Centre	90	370	1800
North	73	366	1700
Control	0	0	0
Sig. level	***	***	***
S.E±	5.1	5.1	38
C.V%	14.5	10.4	5.1

***$P = 0.0001$

Behavior of Autumn Crops

During this season, the southern zone of the alley had the highest reduction of air temperatures and increase of relative humidity (Table 7.1). In contrast, the northern zone of the alley had almost similar changes in the microclimatic factors, with slightly lower value in solar irradiance. On the other hand, the central zone of the alley had the lowest reduction in solar radiation, air temperatures, and lowest increase in relative humidity (Tables 7.1 and 7.3).

In both seasons of 1999 and 2000, the yields of sorghum in the alley plots were increased by 195% and 200% over the control plots as a result of microclimatic improvement in the alleys (Table 7.10). The similarity in microclimatic modification between southern and northern zones of the alley resulted in similar sorghum yields in the two consecutive seasons of 1999 and 2000.

Conclusions

Alley cropping has proven to be a workable and sustainable technology for increasing crop productivity in Northern Sudan. The growth habits of the *A. stenophylla* trees showed high suitability in alley-cropping system because of its capacity to transmit sufficient amount of light through its canopy, and to extract water from levels beyond the root zone of associated agricultural crops. Although the monitored climatic factors

Table 7.10 Yield and yield components of sorghum in different zones of alley and control plots at Hudieba Research Station experimental site during 1999–2000 in Northern Sudan

	Sorghum (1999)		Sorghum (2000)	
Treatments	Plant height (cm)	Yield (Mg/ha)	Plant height (cm)	Yield (Mg/ha)
Control	130	13.0	120	13.3
Southern alley	190	39.0	200	40. 0
Central alley	170	34.7	180	37.7
Northern alley	200	40.0	210	42.3
Sig. level	**	***	***	***
SE±	5.2	1.2	4.7	1.5
C.V %	5.1	6.4	5.7	7.8

**$P = 0.001$; ***$P = 0.0001$

had substantial effects on the crops' behavior and yield, the solar radiation seemed to be the most influential factor responsible for yield reduction or increase in the different alley zones. In addition, the reduction in solar radiation and wind speed reduced evapotranspiration and thereby water use of crop plants. Crop behavior differed greatly according to species and the yields of all crops tested in the alley cropping were significantly higher than those in the control plots. The off-season winter vegetables had benefited the most from the alley-cropping system.

The results of the study clearly indicate that alley-cropping system, using *A. stenophylla* trees, can be adopted to combat desertification, improve microclimatic conditions including water use efficiency, and increase crop yields under the conditions of the semi-desert areas of Northern Sudan. More research is needed to determine the phenology, rate of growth, and morphology of different woody tree species and agricultural crops that dominate in the area for designing more productive and sustainable agroforestry systems.

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Chapter 8
Tree–Crop Interactions in Fruit Tree-based Agroforestry Systems in the Western Highlands of Guatemala: Component Yields and System Performance

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Introduction

Trees grown on farms for their non-timber forest products such as fruits, nuts, and spices constitute the basis for many vibrant and sustainable farming systems throughout the world. Yet, compared to other types of trees, research on horticultural and agronomic management of such trees and systems to optimize total system-yield and understand tree–crop interactions is scarce. Farmers prefer fruit-producing species to other trees for on-farm planting (Raintree, 1992; Franzel et al. 1996), and appreciate the dual contributions of food for consumption (Salam et al. 2000) and the potential for income generation (Delobel et al. 1991; Ayuk et al. 1999). Fruit trees are considered advantageous because of the relatively high returns to labor resulting from low labor inputs (compared with annual crops); moreover, fruit tree-based systems also offer a more uniform distribution of income throughout the year than annual crop systems. However, the relatively "free" availability of forest-based timber- and fuel wood products in some areas are seen as disincentives for growing tree species for those purposes (Hellin et al. 1999).

In temperate regions, the dependence on mechanization (Herzog, 1998) and policies that discourage long-term endeavors (Mary et al. 1999) have limited the extent of fruit-based agroforestry. In tropical and subtropical regions, more often the difficulties are in marketing. Generally, fruit-based systems are economically rewarding with high benefit-to-cost ratios and total system-productivity in fruit tree + annual mixed systems remaining high although individual yields of annual components are commonly reduced relative to sole-cropping (Ashour et al. 1997). Biologically, however, results vary with both yield enhancement and yield suppression occurring depending on complex component–environment interactions. Crop variety,

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

management of crops and trees, and seasonal climate variability all contribute to system performance.

Fruit tree-based agroforestry systems in the altiplano of western Guatemala range from dispersed trees in crop fields through annual crops in semi-managed orchards to homegarden systems. The most common fruit trees in the area are apple (*Malus domestica* Borkh.) and peach (*Prunus* spp. L.), with smaller numbers of numerous other species. Locally, production and quality of apple and peach suffer from suboptimal management and environmental conditions. While improvements in vegetative growth, fruit size, fruit appearance, and total yields could be achieved with better management, only very few management guidelines are available for fruit trees planted amongst annual crops in subtropical highlands.

European pear (*Pyrus communis* L.) is not widely planted by farmers, primarily due to the limited availability of planting materials. Observation of farmers' fruits in 2001 indicated that highland pears were of good quality under low management whereas the appearance of apple and peach suffered from numerous defects. Because pear received equal or higher prices than apple in local markets, pear appears to have good, yet unrealized potential for the region. In spite of the apparent potential of such fruit-based agroforestry systems in the region, the biophysical interactions between pear and other fruit trees and the under-sown annual crops such as maize (*Zea mays* L.) and faba bean (*Vicia faba* L.) have not been studied.

With this background, this study was undertaken to characterize system productivity and evaluate component interactions. The study was based on the hypothesis that integrating pear with maize and faba as mixed crops would produce increases in the efficiency of land use, the biological productivity of the systems, or the economic output of the mixed crops over the monoculture alternatives. Sole cropping (a single species cultivated), intercropping (more than one annual species cultivated together), and mixed cropping (annual + perennial species cultivated together) of maize, faba, and pear were contrasted as three alternatives available to farmers. Mixed cropping of maize, faba, and maize + faba beneath artificial shade structures was also evaluated to differentiate shading (aboveground) effects from moisture and nutrient competition (belowground). Additional findings examining the status of radiation capture, soil water status, and water use by fruit trees will be presented in future publications.

Methods and Materials

Study Area

The study was conducted at the Labor Ovalle Research station in Olintepeque, the department of Quetzaltenango, Guatemala (14° 30′ 50″ N, 91° 30′ 50″ W) at an altitude of 2390 m above sea level. Annual mean temperature is 13.8 °C, mean daily maximum is 21.9 °C, and mean daily minimum 6.0 °C (1971–2002). The mean frost free growing period (defined as $T > 0.0\,^{\circ}C$) is 210 days per year and ranged from 119 days in 1978 to 277 days in 1999. Total solar radiation during 2002 was 7224 MJ m^{-2} $year^{-1}$. Mean annual precipitation is 816 mm $year^{-1}$, with a maximum of 1085 mm in 1998 and a minimum of 623 mm in 1987. During the two seasons, precipitation, solar radiation, temperature, pan evaporation, and soil moisture were recorded daily using standard sensors and Campbell Scientific (Logan, Utah) data loggers. A daily index of estimated moisture availability was calculated as the cumulative difference between precipitation and pan evaporation. The index was set daily to 0.0 when the cumulative trend was negative with the effect that any precipitation event in excess of evaporative demand in a 24 h period gives a positive value on the index.

The local relief is mountainous valley bottoms surrounded by rugged ridges and ravines previously occupied by subtropical lower montane semi-humid forest. The soils are entisols in the Quetzaltenango series and cultivation was on heterogeneous clay loams with good drainage. The experiment was conducted during 2002 and 2003 in a field known as El Tecolote that had previously been used for fruit tree varietal trials and semi-commercial fruit production.

Plant Materials

Maize and faba bean were selected as the two annual crops and European pear as the deciduous fruiting perennial. The study was conducted in or near the center of diversity for maize in highland Mexico and Guatemala. The selected maize cultivar (San Marceño Mejorado: ICTA) differs substantially from those grown in lowland tropics or temperate zones. It is taller with a higher number of leaves at anthesis, is often weakly rooted, and has multiple ears per stem. Morphologically, the leaves are long, broad, and droop substantially; are often densely pubescent; and they contain substantial quantities of anthocyanin, giving them a purple color. Physiologically, highland varieties may have lower optimal and base temperatures for growth and development (Ellis et al. 1992). It is a yellow, open pollinated population selected from crosses of locally collected landraces San Marceño and Chivaretto. In 2002, under common local management regimes, San Marceño Mejorado yielded 5200–6300 kg ha^{-1} from a stand with an average height of 2.65 m to the base of the tassel. The crop required 217 days from planting until the ears reached the low moisture content favored for harvesting.

Faba bean's (*Vicia faba* L. var. *faba*) center of genetic diversity is in the Near East or Central Asia (Ladizinsky, 1975). The list of common names is diverse including field bean, horse bean, broad bean, faba bean, fava bean, windsor bean, gourgane, and haba among others (Weirsema and León, 1999). The crop has a long history of cultivation and adaption in the highlands of Guatemala since it was introduced during the Spanish colonization. ICTA Blanquita was chosen following selection from numerous landraces present in regional markets. The cream colored seeds, containing a low percentage of yellow or purple colored beans, are described as larger than "unimproved" varieties with a 1000 seed mass of 1.9 kg. Under locally common management regimes, the cultivar develops a leaf area index (LAI) of approximately 2.75. At maturity, ICTA Blanquita may have upwards of 12 tillers and a height > 2.0 m. In 2002, the faba crop required 162 days (175 days in 2003) from planting until harvest.

The origins of pear trees (*Pyrus communis* L.) can be traced to Central Asia, Eastern Europe, and Northern Africa. Two cultivars were included in the study, Bartlett or Pera de jugo and Ayres (also known as Tennessee). Both varieties had been grafted to *Pyrus calleryana* rootstocks. In the remainder of this paper, the common name pear or the varietal names are used to refer to a grafted combination of *Pyrus communis* over *Pyrus calleryana*. Without pruning, the upright trees can grow to 14–16 m, but rarely are they allowed to exceed 4–6 m. Trees were 8 years old at the time of this study and were being managed with a grass and weed understory having been fertilized and ring-weeded annually.

Experimental Design and Establishment

A replicated completely randomized block design was established in an existing stand of pear trees, by incorporating annual intercrops and artificial shade structures. Pear trees were removed to permit the establishment of non-tree controls (annual crop). Pear + maize + faba, pear + maize, pear + faba, and sole pear treatments (tree control) were assigned randomly to plots containing trees. Maize + faba, sole maize, sole faba treatments, each with and without artificial shade structures were assigned randomly to the remaining six plots in each of the five blocks.

Cables to facilitate data collection were installed and buried in 1.0 m-deep trenches dug around the perimeter of experimental plots. The plots were 8.0 m long and 5.0 m wide. Each contained four pear trees (two of each variety at a spacing of 2.5 m), four shade structures, or no shading. The annual crops were sown on 13 May 2002 and 10 April 2003 at 1.0 m between rows and 0.6 m within rows, with sole maize treatments receiving five seeds (81,000 plants ha^{-1}), sole faba treatments receiving three seeds (48,700 plants ha^{-1}), and intercrops treatments receiving five seeds of maize and three seeds of faba. Within fruit tree only controls, planting sites were cultivated (hand-hoe tilled) but not sown to any crop.

Pyramidal artificial shade structures were constructed from pyramidal steel bar frames covered with 30% neutral density shade fabric. Canopy height, crown base height, and mean maximum crown extension were measured on the live trees in the plots, and were used to determine the dimensions of the structures, which were 2.62 m and 2.76 m in height and 0.8 m and 1.10 m in diameter for Ayres and Bartlett, respectively.

Root suckers on pear trees were trimmed throughout the experiment at monthly intervals. Suckering was more prevalent beneath Bartlett than Ayres. Stem and branch pruning was not conducted during the experiment as growth was deemed insufficient to require canopy management. All trees were painted with a slurry mixture of lime in February. In both 2002 and 2003, granular fertilizer (15-15-15) was applied at the base of each trunk at the rate of 0.25 kg per tree with an area-based application rate of 250 kg ha^{-1}. Additionally, both mixed-cropping and sole-tree treatments received fertilizers as described below. Fruit set did not appear to be excessive and thinning was not conducted. Fruits that abscised before harvest were not collected, nor were they considered except in fruit set counts.

Tree understory was maintained weed free year-round. When crops were present, this was as part of weed management for the associated crops. Sole tree plots received identical weed management as mixed-cropping plots. In April and May 2002, affected trees were spot treated with Thiodan (endosulfan) for minor aphid infestations.

Fertilization was performed at 26, 60, and 85 DAP (days after planting). At 26 DAP, all plants were sprayed with a complete foliar fertilizer (Avantis complete liquid) containing the following formulation: N = 9%, P_2O_5 = 9%, K_2O = 7%, Mg = 0.01%, S = 0.16%, B = 0.01%, Cu = 0.01%, Fe = 0.01%, Mn = 0.01%, Mo = 0.005%, Zn = 0.005%, Inert - 74.78%. At 60 DAP, granular fertilizer (15-15-15) was applied at a rate of 360 kg ha^{-1} using measured quantities at each planting site. At 85 DAP, granular urea (45-0-0) was applied at 360 kg ha^{-1} to treatments containing maize by the same technique used at day 65. Granular 15-15-15 was applied to sole faba treatments in place of urea. The application rates of granular fertilizer were at the upper range of the practices normally followed by local producers with total annual applications totaling 216 kg ha^{-1} N for maize and maize + faba combinations, 108 kg ha^{-1} N for sole faba crops and an additional 37.5 kg ha^{-1} N where annuals were mixed with pear trees.

Fruit Tree Growth and Yield Measures

Diameter and height growth: Trunk diameter was measured at monthly intervals using digital calipers and squares of Plexiglas (1.0 cm^2) epoxied to the trunks at a height of 22 cm. Crown heights were measured from the trunk base to the highest branch tip during the early-, middle-, and late season and maximum crown extension was measured through the line of the trunk.

Vegetative and floral development: Trees were observed weekly for vegetative bud break and flowering and were noted with <5 fully expanded leaves or >5 leaves. The presence of recognizable, no longer quiescent, floral buds was noted. Open flowers were defined as those at all stages from when the reproductive parts were visible in the center of the expanding petal whorl until all petals had abscised. The number of flowers was recorded weekly for each tree. Fruit in which all petals had separated from the calyx and the ovary had swollen to the size of approximately 5 mm were recorded each week from the beginning of flowering until flowering had ceased and fruit number stabilized.

Fruit yield: All fruits were harvested on the same date, tree-wise, and sorted into three classes based on size by a "grader" with experience in local fruit grading practices. Grade-one fruits were defined as the largest size class of fruits for market purposes; grades two and three were the next lower categories. Fruit mass and number for each size class were recorded and a representative fruit from grades one and two selected for further analysis. Eight days post-harvest, the sugar or soluble solids content (percent brix) of expressed juice was measured with a temperature compensated refractometer (Model 30387, Ben Meadows Company, Janesville, WI, USA).

Crop Responses

Yields of each annual crop under different treatments were assessed. Two planting sites (1.2 m^2 total) distant from the canopy were harvested and labeled as "far" samples, and two sites were from beneath the canopy of two fruit trees (1.2 m^2 total) and marked "close." For faba, pod numbers, weight of air-dried pods and seeds were recorded, and yields were expressed at 12% moisture content (after determining moisture using a Dole 400 moisture meter with the soybean scale). The remainder of the net plot was harvested in bulk 162 DAP in 2002 and 175 DAP in 2003 and was combined with close and far subsamples to determine net plot yield. Maize was harvested 215 DAP in 2002 and 217 DAP in 2003. As with faba, both close and far sites were subsampled for distance-dependent yield analysis, and yield was reported at 12% moisture content.

Data Analysis

While the experimental design was a completely randomized block design, because of the structural or intentional effects and intercropping nature of the experiments, the statistical analysis reduces to a series of factorial experiments. Growth and yield effects in maize and faba were analyzed as factorials (2 × 3) with two levels of crop associates (sole crop or maize + faba intercrop) and three levels of environmental conditions (without trees, with pear trees, and with artificial shade structures).

For assessing crop effects on fruit tree performance, the effects were analyzed as a factorial (2 × 4) with two varieties (Ayres and Bartlett) and four environments (sole maize, sole faba, maize + faba, and clean cultivation). Standard statistical norms of $\alpha < 0.05$ were used in all analyses and multiple comparisons of means were made with Tukey's HSD to maintain acceptable and conservative confidence levels. SAS statistical software (SAS Institute, Cary, North Carolina) was used for all ANOVA and mean separation tests.

Using the land equivalency ratio (LER) and the area time equivalency ratio (ATER), the relative yields of maize + faba, pear + maize, pear + faba, and pear + maize + faba systems were assessed (Equations 1 and 2). Further evaluation of relative yield ratios (the component ratios of LER) was made graphically to examine the nature of productive coexistence in mixtures with LER > 1.0.

$$LER = \frac{Y_i^1}{Y_s^1} + \frac{Y_i^2}{Y_s^2} + \frac{Y_i^3}{Y_s^3} \qquad (1)$$

Subscripts s and i indicate sole and intercrop yields, superscripts indicate components

$$ATER = \left(\frac{t_s^1}{t_i^1}\right)\left(\frac{y_i^1}{y_s^1}\right) + \left(\frac{t_s^2}{t_i^2}\right)\left(\frac{y_i^2}{y_s^2}\right) + \left(\frac{t_s^3}{t_i^3}\right)\left(\frac{y_i^3}{y_s^3}\right) \qquad (2)$$

Subscripts s and i indicate sole and intercrop yields (y) and crop durations (t), superscripts 1 and 2 indicate the individual system components or crops.

Relative yields for pear, maize, and faba were calculated using the yields of each component as sole crops and their yields as either intercrops or part of a mixed crop system. The components were systematically graphed and the interaction effects of each component pair in each cropping regime were interpreted (Figure 8.3).

Economic valuation of fruit tree-based and intercropping systems was calculated using measured yields for each component and market prices for 2003. Thus, economic values did not compare potentially differential labor or input costs. Yield values were calculated based on 1.0 ha of the system. For sole crop comparisons, this assumes 50% land allocation to each component for intercropping or 33% land allocation for mixed cropping. Therefore, a 1.0 ha intercrop of maize + faba was compared with the sum of 0.5 ha each of sole cropped maize and faba.

Direct comparisons of biological yields provided an alternative method to compare the disparate outputs of the alternative cropping options. Valuation of system productivity was made by conversion of economic yields to their glucose-equivalent production costs by estimating the carbon skeleton costs and the energy requirements to manufacture each yield component and calculate the equivalent amount of glucose per unit yield, a uniform basis for comparisons of the "biological yields" (Penning de Vries et al. 1983). The standard composition of each type of yield (maize, faba bean, or fresh pear) was converted to percentages of dry weight found as proteins, lipids, carbohydrates, and ash for this analysis.

Results and Discussion

Annual Weather Variability

Clear differences were observed in precipitation and potential evaporation (PET) between 2002 and 2003. During the 2002, total precipitation was 794.0 mm compared with 669 mm in 2003. The total potential evaporation during the same period was 1459.0 mm in 2002 and 1376.0 mm in 2003. The differences in potential evaporation during the cropping season in 2002 and 2003 were minor and cannot explain the behavior of the soil wetting index (Figure 8.1). While the early limitations on

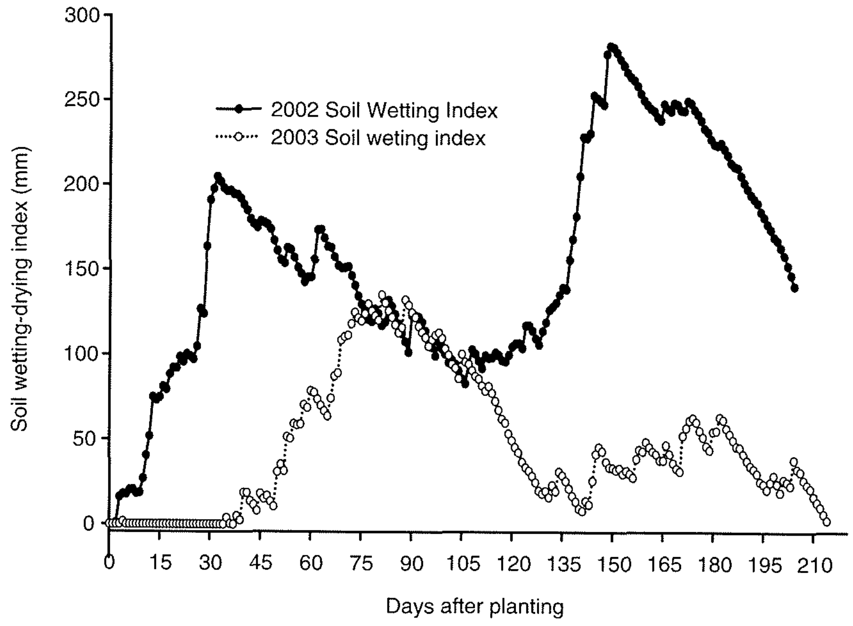

Figure 8.1 Seasonal differences in available moisture expressed with a soil wetting index defined as cumulative [daily precipitation - daily potential evaporation] in Quetzaltenango, Guatemala

soil water in 2003 are a reflection of an earlier (pre-rain) planting date, late in the rainy season the amount of precipitation in excess of PET is dramatically reduced and indicates the much greater limitation of water for all treatments during 2003.

Fruit Tree Responses

Flowering phenology and fruit set: In 2002, the period of maximum flowering in both varieties of pear trees occurred simultaneously; but Ayres began flowering much earlier than the peak and Bartlett continued flowering during an extended period afterward. In 2003, flowering period in Ayres was short due to a series of freeze events during the period. Flowering in Bartlett appeared unaffected by frost events beyond the timing of the start of flowering (Figure 8.2). During both years, the number of fruits set per tree for Bartlett eventually surpassed that of Ayres. Flowering and fruit set were not impacted by understory cropping treatments.

Tree diameters and heights: Tree trunk diameter and height were not affected by the understory crop treatments; however, vegetative growth was greater in Ayres than in Bartlett during both years: mean height increase was 0.27 m for Ayres and 0.18 m for Bartlett in 2003 and 0.06 m and 0.02 m, respectively in 2002. It is likely that the production of "suckers" by the rootstock beneath Bartlett may have caused some of the differences in growth between the varieties. The significant differences in height growth between 2002 and 2003 may have been influenced by changes in light quality commonly associated with reflection from associated crops (Cassal et al. 1997). Also contributing were the improved conditions for tree growth under all experimental alternatives compared with the pre-experiment weed understory.

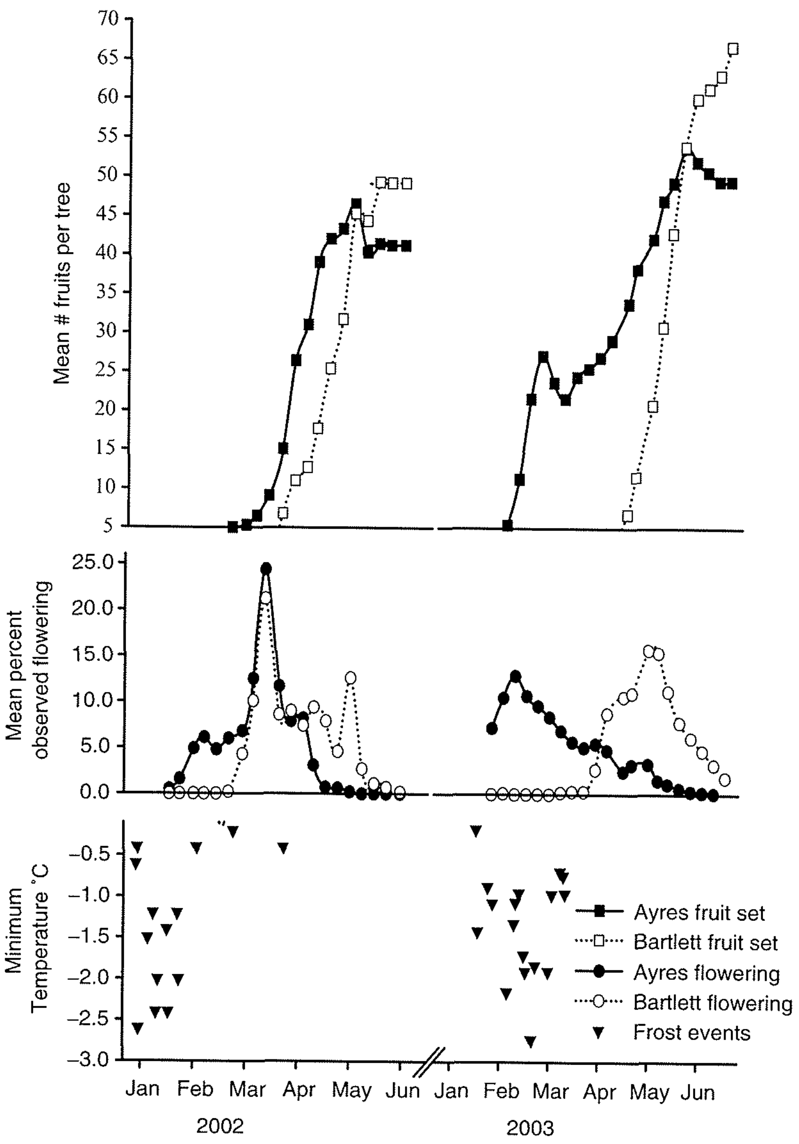

Figure 8.2 Flowering phenology and fruit set of two pear varieties in 2002 and 2003 at Labor Ovalle, Quetzaltenango, Guatemala and their relation to subfreezing temperatures occurring during both years

Growth often relies on factors accumulated during the previous year (Quartieri et al. 2002) and 2003 responses were due primarily to the previous season's (2002) conditions, compared with growth in 2002 as a response to the previous grass and weed understory. While the lack of a cropping effect in 2003 suggests that adequate vegetative growth may occur in fruit trees growing in concert with annual crops, results from two seasons are insufficient to conclude that annual crops will not eventually depress vegetative growth below acceptable levels. The long-term impact of mixed cropping on tree height growth remains inconclusive, but the use of pruning as a tree management may offer an effective response.

Fruit yield: The total fresh fruit yield per tree in 2002 was not affected by the understory conditions imposed in the spring of 2002. During 2003, fruit yield per tree was higher with faba associates and the control treatment compared with maize (Table 8.1). Bartlett yields were higher than Ayres during both years. Clearly, there was a depressive effect observed in 2003 associated with maize and most likely is a response to 2002 treatments. The total number of fruits per tree was not reduced by the cropping conditions in the understory during 2002 or 2003. Again, during both years, the number of fruits per tree was higher in Bartlett (57.6–67.4) than in Ayres (40.5–41.4). In both 2002 and 2003, flowering by Ayres may have been inhibited by the pattern of freeze events resulting in lower fruit set than Bartlett, and a trade-off between reproductive and vegetative growth was evident in the two varieties where reproductive growth was favored over vegetative in Bartlett and the reverse was true in Ayres. This is well explained by the interaction of early flowering in Ayres (Figure 8.2) and reduced reproductive potential likely due to the local climatic conditions. Ayres began each growing season with fewer reproductive sinks relative to vegetative and excess photosynthates were allocated to enhanced vegetative growth. Berman and Dejong (2003) observed similar changes in allocation between reproductive and vegetative organs in peach. There were no indications that either cultivar was better suited for growing with annual crops.

Table 8.1 Fruit yield (fresh weight) of two grafted pear varieties under four understory management regimes during 2002 and 2003 at El Tecolote, Labor Ovalle, Guatemala

	Var. Ayres ($g\ tree^{-1}$)		Var. Bartlett ($g\ tree^{-1}$)		Fruit mass ($g\ tree^{-1}$)	
Understory trt.					0	0
	2002	2003	2002	2003	2002	2003
Maize	5246	3290	8709	8615	6978	5952 a
Faba	4109	4890	8709	13464	6409	9177 b
Maize + faba	4163	3360	7823	7747	5993	5553 a
Control	4146	4493	8064	9561	6105	7027 ab
0	4416 a	4008 y	8326 b	9847 z		

In 2002, main plot (understory treatment) effects were not significant; subplot (variety) effects were significant ($p < 0.001$).

In 2003, main plot (understory treatment) effects were significant ($p < 0.001$), subplot (variety) effects were significant ($p < 0.001$).

Means separation within years by Tukey HSD ($\alpha = 0.05$). Yearly means followed by the same letter are not significantly different.

Fruit Quality: Pear trees intercropped with maize produced the smallest fraction of grade-one fruits compared with faba intercropping or clean-cultivation treatments. Trees underplanted with faba, produced a greater proportion of first-grade fruits but the advantage over clean cultivation was not significant. (Table 8.2). During both years, Bartlett produced higher fractions of grade-one fruits under all treatment conditions than Ayres.

Competition for water has been shown to reduce fruit size owing to limitations in cell division and later in cell expansion (Caspari et al. 1994; Naor et al. 1999) and the competitive effects of grasses, such as maize, with fruit trees are well known (Kumar et al. 2001; Tworkoski and Glenn, 2001). It can be surmised that, at the experimental planting densities under Guatemalan climatic conditions, reduced fruit size and mass are likely to be observed when interplanted with maize. This reduction is consistent with the expected outcome from competition for soil moisture. In contrast, trees underplanted with faba bean had enhanced growth and production of grade-one fruits, although the advantage over clean cultivation was not significant (Table 8.2). Although any nitrogen contribution by faba beans was not experimentally determined, the faba plants were heavily nodulated, suggesting a possible role for N_2 fixation in the observed results. Canopy shading may also contribute to reductions in fruit size in pear (Kappel, 1989). Where pear trees were interplanted with maize, tree crowns were shaded relative to diffuse, morning and afternoon light by mid-season. Therefore, the possibility that fruit size reductions were influenced by a combination of competition for light and water cannot be excluded, particularly as in treatments with the smaller statured faba, no shading comparative to that between maize and pear occurred.

Fruit soluble-solids were unaffected by the understory treatments in 2002 (Table 8.2) but were higher in the sole pear treatment than in treatments containing maize in 2003. Soluble solids in fruit grown with faba were intermediate between those of fruit grown with maize and the higher levels in the sole pear treatments.

If carbohydrates are limited during fruit filling, it should be reflected in terms of either decreased sugar content of fruit or decreased vegetative growth. While means separation was incomplete, percent brix was greatest with the clean cultivated understory and lowest where maize was present as an associate (Table 8.2). The lower brix values within maize treatments suggest tree – crop competition was sufficient to limit overall tree carbohydrates – a conjecture, which additional data are needed for proving.

In this study, reproductive growth of fruit trees was negatively affected where underplanted with maize crops, but enhanced in association with faba crops in terms of soluble-solids content and yields of grade-one fruits (Table 8.2), and total fruit mass (Table 8.1). The few studies that have reported on impacts of understory vegetation on fruit trees primarily consider weeds and grasses or leguminous crops (Anderson et al. 1992; Lipecki and Berbec, 1997). Competitive effects against seedling or immature trees have been found, at a time when it can be assumed that there is little to no differentiation in root or canopy space. However, mature fruit

Table 8.2 Grade-one fruits and percent soluble solids (percent brix) of two grafted pear varieties under four understory management regimes at El Tecolote, Labor Ovalle, Guatemala

	Grade-one fruits (percent of total)				Soluble solids (percent brix)				Grade-one fruits (% of total)		Soluble solids (% brix)	
	2002		2003		2002		2003		0	0	0	0
Trt.	Ayres	Bartlett	Ayres	Bartlett	Ayres	Bartlett	Ayres	Bartlett	2002	2003	2002	2003
Maize	21.8	40.0	6.6	53.6	11.3	10.5	12.0	11.0	30.9 a	30.1 a	10.9	11.4 x
Faba	35.6	48.0	28.8	86.1	11.1	11.2	12.3	11.9	41.8 b	57.5 b	11.2	12.1 xy
Maize + faba	20.0	45.5	13.3	48.4	11.0	10.8	11.5	11.2	32.7 ab	30.8 a	10.9	11.4 x
Control	31.0	50.6	29.6	68.3	11.6	11.3	12.9	12.0	40.8 ab	48.9 ab	11.4	12.4 y
0	27.1 y	46.0 z	19.6 j	64.1k	11.3	11.0	12.1 a	11.5 b				

In 2002, main plot (understory management) effects for grade-one fruits were significant ($p < 0.05$), and subplot (variety) effects were significant ($p < 0.001$).

In 2003, main plot (understory management) effects for grade-one fruits were significant ($p < 0.001$), and subplot (variety) effects were significant ($p < 0.001$).

In 2002, main plot (understory management) effects for percent brix were not significant, subplot (variety) effects were not significant.

In 2003, main plot (understory management) effects for percent brix were significant ($p < 0.001$), subplot (variety) effects were significant ($p < 0.001$).

Yearly means followed by the same letter are not significantly different by Tukey HSD ($\alpha=0.05$).

trees are also affected, potentially due to low root densities. Yield depression in one component must be tempered by the response from the overall system since complete complementarity between components for all required growth factors is unexpected and unrealistic.

Crop Responses

Maize yields: Grain yield was not affected by the three overstory environment treatments in 2002, whereas in 2003, sole-crop maize treatments had higher yields than crops among pear trees. In 2002, maize grown in association with faba yielded more than in sole crop regardless of overstory environment; however this effect was not observed in 2003 (Table 8.3). Additionally, ear number was unaffected by overstory treatments indicating that mixed cropping impacted growth but not necessarily reproductive development (data not shown).

While performance in 2002 was influenced to some extent by the previous seven years' management, in 2003, the depression of maize grain yields was much greater

Table 8.3 Maize and faba yield from sole crops (M or F) and intercrops (M + F) under overstory environments of pear trees, artificial trees, and no overstory (control) in El Tecolote, Labor Ovalle, Guatemala

	Maize grain (Mg ha^{-1})				Faba seed (Mg ha^{-1})				Maize grain (Mg ha^{-1})	
	2002		2003		2002		2003		0	
Overstory environment	M	M + F	M	M + F	F	M + F	F	M + F	2002	2003
Pear overstory	5.5	5.4	7.1	8.2	1.5	0.7	1.9 j	0.2 z	5.5	7.7 a
Artificial overstory	5.0	5.8	11.0 x	6.9 y	1.9	0.6	2.6 k	0.2 z	5.4	9.0 ab
Control	5.4	6.2	9.8	11.0	1.9	0.6	2.5 k	0.2 z	5.8	10.4 b
0	5.3 a	5.8 b	9.3	8.7	1.8 a	0.6 b	2.3 a	0.2 b		

In 2002, overstory environment effects on maize were not significant, and cropping effects were significant ($p<0.001$).

In 2003, overstory environment effects on maize were significant ($p<0.05$), and cropping effects were not significant.

In 2003, an overstory × cropping interaction effect on maize was significant ($p<0.001$). Analysis at fixed levels of overstory environment indicates that under artificial canopies sole cropped maize had higher yields than intercropped.

Overstory environment effects for faba were not significant, but cropping effects were significant ($p<0.001$).

In 2003, interaction effects for faba were significant ($p<0.05$), cropping effects were significant ($p<0.001$), and overstory effects were significant at fixed levels of cropping ($p<0.001$); where faba was the only annual, yields were lowest beneath pear trees.

Means within a year followed by the same letter are not significantly different by Tukey (HSD) ($\alpha=0.05$).

with fruit trees than with shade structures (Table 8.3), strongly suggesting the existence of increased belowground competition as a causal factor.

The potential yield loss of maize grain due to intercropping or shading is estimated as 380kg ha^{-1} year^{-1}. On the farm scale, this translates to a loss of 16.8kg cuerda^{-1} (1.0 cuerda = 441 m^2, the standard area measure for agriculture in highland Guatemala. Before shelling (mean 69%), this potential yield loss approaches a difficult-to-detect level of loss in total yields, particularly if the field is not uniformly dedicated to fruit + maize mixed cropping.

Maize intercropped with faba had higher grain yield (790kg ha^{-1}) over sole-cropped maize (Table 8.3) during the first year irrespective of the presence of trees or shading. This advantage was not observed during the second year. It is possible that soil moisture availability in 2003 was sufficiently reduced that maize + faba competition for soil water had a larger impact than the previously observed positive effect with faba. The reduced maize yield observed with pear trees are consistent with common observations in farmers' fields where crop growth is visually depressed in proximity to mature fruit trees, and can clearly be attributed to the impacts water and/or nutrient competition as discussed above.

Faba yields: Faba yields were unaffected by the overstory treatments in 2002, but a significant interaction was detected in 2003: with faba alone beneath the overstory, yields were depressed beneath pear trees compared with artificial shade structures or no overstory. Cropping maize + faba as the understory crop resulted in a decrease in faba yields (Table 8.3) regardless of overstory environment or year. The intercrop of maize + faba reduced the number of faba pods at harvest as compared with sole faba stands (data not shown).

The faba yield loss associated with pear was small in magnitude compared to that observed with maize where yields were consistently and substantially depressed in intercropping situations (about 34% yield reduction compared with sole stand). In 2003, faba yields without maize associates were significantly greater than 2002 indicating the superior conditions for growth in 2003. It may be noted that maize yields were also similarly higher in 2003 than 2002. Yet, in 2003 in association with maize, both the previously observed positive maize response was absent and the intercropped faba yields declined compared to 2002. Since a principal difference between the two seasons is related to water availability, we speculate that excess competition for below ground resources can explain this. The increased maize growth (Table 8.3) and reduced water availability (Figure 8.1) may have reduced faba performance during the critical flowering period leading to low pod numbers and reduced yields and is consistent with Plies-Balzer et al. (1995).

In contrast to maize, the number of pods per faba plant was depressed where maize was associated with the faba crop. As expected, faba yields were not greatly impacted by overstory shading by fruit trees or shade structures, rather the yield declines observed beneath pear in 2003 are potentially the results of competition for belowground resources by pear trees. This study provides little basis for partitioning the causal mechanisms between soil moisture and nutrient competition. Biological fixation of N_2 in faba is reduced dramatically by relatively mild reductions in water potential (Guerin et al. 1990). Additional research is warranted to evaluate

the extent to which contributions to the system pool of N by faba are responsible for the observed yield shifts and to what extent associated crops and climatic conditions altered this contribution.

Land Equivalency and Area Time Equivalency Ratios

In terms of LER and ATER, intercropping and mixed cropping systems at the El Tecolote site provided a substantial yield advantage over similarly managed monocultures. Mixed cropping of pear + maize + faba had the highest LER: 2.98 in 2002 and 3.03 in 2003 (Table 8.4). All mixed crops and intercrops showed relative yield advantages. The additive intercrop of maize + faba showed the least advantage: LER of 1.45 in 2002 and 1.37 in 2003. The existence of LER values > 1.0 shows that increases in returns to land area were possible using the crops studied. Increased use of available resources by the addition of components with a degree of niche separation is a possible explanation, however the expansion of the resource pool, i.e. N_2 fixation by leguminous crops cannot be ruled out.

ATER calculations also showed that the mixtures produced yield advantages relative to monocultures. The greatest advantage was observed in mixed cultivation of pear + maize + faba bean, with ATER 1.99 in 2002 and 1.93 in 2003. The least advantageous system was maize + faba bean intercropping that had an ATER of 1.37 in 2002 and 1.18 during 2003 (Table 8.4). Though some benefits in each of the cropping options were due solely to increased duration of crops on the land area, substantial improvements in relative yields to land area remained and must be considered as real benefits achievable from interactions in mixed systems. The LER-ATER analysis supports the previous observation that performance in mixtures was reduced in 2003 compared with 2002 and reflects the greater potential of sole crops under the conditions in 2003.

Examination of relative yield ratios of the individual components, as calculated for LER, indicated that the maize component did not suffer substantial negative impacts (reduced yield relative to sole crop yields) with either faba or pear as associates.

Table 8.4 Land equivalency ratio (LER) and area time equivalency ratio (ATER) of mixed cropping, intercropping and sole cropping systems of pear, maize, and faba bean in on-station trials to evaluate agroforestry technologies in western Guatemala

	LER		ATER	
	2002	2003	2002	2003
Maize + faba intercrop	1.45	1.19	1.37	1.18
0Pear + maize mixed crop	2.16	1.59	1.74	1.29
Pear + faba mixed crop	1.87	2.00	1.041	1.61
Pear + maize + faba mixed crop	2.98	3.03	1.99	1.93

ATER based on 162 (2002) or 175 (2003) days for faba, 215 (2002) or 217 (2003) days for maize, and 365 days for pear.

However, mixed cropping with pear trees did not increase maize yields in pear + maize or pear + maize + faba mixed cropping either (Figure 8.3).

Maize in maize + faba intercropping had higher yields that sole-crop maize, but the yield-enhancing effect was diminished where pear was included in the mixture. Faba suffered strong yield depression in the presence of maize; however, the effect of pear on faba yield was neutral where maize was not present (Figure 8.3). Response of pear to pear + maize and pear + faba mixed crops was variable, in that maize generally reduced pear yields relative to sole pear while in pear + faba mixed cropping, pear yields were improved (Figure 8.3 and Table 8.2).

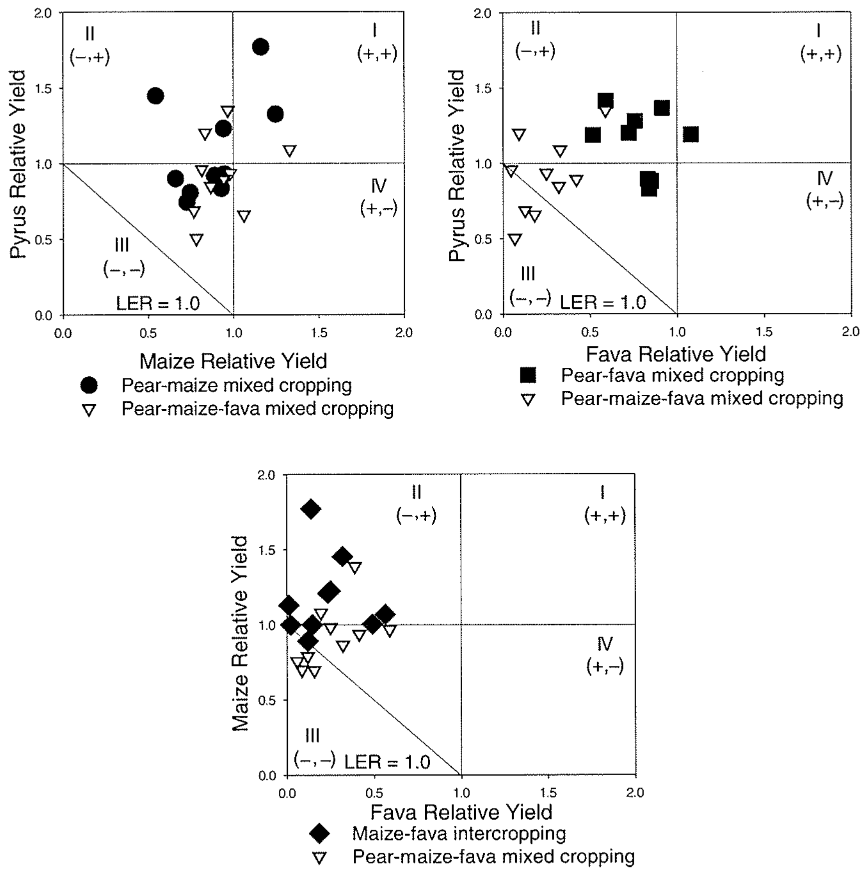

Figure 8.3 Relationships of the relative yields of three components during 2002 and 2003 under mixed or intercropping patterns at high densities relative to regional practices. The four quadrants (I, II, III, and IV) represent possible interactions; with II and IV representing monopolistic competition by one of the system components. Quadrant I represents synergistic interactions and III indicates inhibitory interactions. The diagonal line (LER = 1.0) represents the limits of productive coexistence in fruit tree-based agroforestry. Systems that are located to the left of the diagonal line are detrimental, whereas, systems to the right of the diagonal provide an advantage relative to sole cropping of the components

Inclusion of pear trees as overstory species did not cause any advantage for maize or faba, indicating that any improvements in understory light or temperature climates were less important than the competitive belowground interactions. Yields of both maize and pear were greater in the presence of faba; however the effect was notably less when a third component was present. It is likely that mixed cropping altered the partitioning of growth resources such as radiation, water, and nutrients to specific components. Detailed examination of the impact of mixed cropping on resource absorption and use will be presented in forthcoming publications.

Mixtures of maize, faba, and pear produce both increases in total systems yields as well as shifts in the performance of individual components. Because components differ in both their economic and nutritional value, it is possible to change crop proportions in mixtures and realize increased relative yields yet produce an overall economic or nutritional loss from the perspective of small farmers. As LER and ATER alone are inadequate to show potential benefits, the final section evaluates system productivity from economic and energetic perspectives.

Economic Response of Fruit-Tree-Based Agroforestry

Mixed-cropping and intercropping systems are difficult to compare directly with sole crop counterparts, as yield comparisons must be made between alternative products. Here, yield of maize, faba bean, and pear were converted to corresponding economic values using market values in late 2003. Mixed cropping of maize + faba + pear had the most valuable harvests of the studied systems showing an economic advantage of 124.2% over sole cropping of each of the three components. Sole cropping of maize had the lowest economic return (Table 8.5). The additional values of stover for fodder and tree litter as organic matter recycled and potentially not extracted from adjacent forest areas were not considered. For this reason, estimates of economic output are slightly lower than what producers may actually perceive.

During the experiment, intercropping or mixed cropping did not necessitate any labor activities or inputs additional to what were needed or done for sole crop situations. Mixed cropping and intercropping costs were additive, in the sense that the production costs for the combined systems were equal to the sums needed for each component when grown as sole crops. However in practice, reduced total expenditures on labor in intercropping and mixed cropping systems may occur. A clear example is the labor costs or herbicide expenses related to clean cultivation where the presence of annual crops limited weed growth and reduced the amount of weeding required beneath fruit trees. The direct comparisons between economic outputs (Table 8.5) are gross returns which do not consider the production costs and show comparative economic potential rather than absolute farmer benefits.

The economic output of the systems is consistent with LER-ATER where pear + maize + faba mixed cropping had the greatest yield potential and maize + faba intercropping excluding sole crop alternatives the least (Table 8.5). Pear + faba mixed cropping was slightly more remunerative than pear + maize mixed cropping.

Table 8.5 Gross value of economic yield and glucose-equivalent yields based on standard yield compositions of sole cropping, intercropping, and mixed cropping of maize, faba bean, and pear in 2002 in the western highlands of Guatemala

Cropping system			Yields	Gross value of economic yield Quetzales (Q) ha^{-1} (1.00 $US = Q 7.85)		Material and growth cost of economic yield (kg glu ha^{-1})	
	Q kg^{-1}	kg glucose kg^{-1} product	(kg ha^{-1})	Intercrops	Sole crops	Intercrops	Sole crops
Maize	1.87	1.49	5,447		10,187		8,117
Faba	7.70	1.69	1,849		14,233		3,124
Pear	11.00	1.30	1,220		13,420		1,586
Maize + faba			6,205 maize 578 faba	16052	12,210	10,222	5,620
Pear + maize			5,526 maize 1,395 pear	25,679	11,804	10,048	4,851
Pear + faba			1,516 faba 1,280 pear	25,756	13,827	4,227	2,355
Pear + maize + faba			5,400 maize 650 faba 1,198 pear	28,283	12,613	10,703	4,276

Economic and glucose-equivalent yields based on cropping of 1.0 ha.
Sole cropping comparisons of intercrop systems based on 0.5 ha of each component and 0.33 ha for mixed cropping.
Fruit values based on 200 trees ha^{-1}.

Further research is needed, however, to ascertain whether these relative advantages are stable at lower crop densities. The crop densities in this experiment were at the upper limits for crop densities for maize and pear and high for faba intercrops. Similar high economic returns at high plant-densities in alley crops of maize, beans, and walnut (*Juglans nigra* L.) have been observed in temperate North America; however no consideration was given to potentially valuable nut yields under those conditions (Benjamin et al. 2000).

Biological Response of Fruit-Tree-Based Agroforestry

Comparison of glucose-equivalent yields indicated that mixed cropping of maize + faba + pear had the highest system productivity in terms of harvested economic yields. The lowest glucose-equivalent yields occurred in the sole cropping of pear (Table 8.5). Sole cropping of maize allowed the harvest of five times greater glucose-equivalent yields than sole cropping of pear, and was nearly twice as productive as mixed cropping of pear + faba. All mixed cropping or intercropping patterns with maize as a component were essentially equivalent in their productivity.

The yield potential of highland maize in the local environment was highlighted in as much as it was 160% more productive than a comparable sole crop of faba bean and 400% greater than clean cultivated fruit trees at 200 trees per hectare (Table 8.5). In order for harvests from fruit tree-based agroforestry to be more energetically productive than sole cropped maize, they must include maize as a component as mixed or sole cropping of pear and faba had lower productivity as measured by glucose-equivalent yields. We did not consider crop by-products such as root remnants, maize, and faba stover, or tree vegetative biomass and therefore it should not be construed as an adequate measure of overall system productivity. Because maize stover is valued and harvested for fodder, the analysis of harvested yields is incomplete; systems with maize components are clearly more productive from producers' perspectives.

Concluding Remarks

In order to be successful, agroforestry systems for smallholder farmers should produce their benefits by exploitation of additional available resources that are unused in tree-less systems. It may be overly optimistic to expect that additional components can be inserted into an efficient agronomic system with no overlap or competitive resource capture. Cannell et al. (1996) suggest that losses to one component due to competition will only be considered important by producers relative to the value of the additional products produced. The implication is that perennial components with high value yields over a time frame acceptable to producers should enjoy greater adoption than lesser-valued products or those with excessive delays before products are mature.

In the Guatemalan altiplano, fruit producing trees are valued for potential fruit sales and/or household consumption of the fruit. In the absence of on-farm production, fruit may not be available to families. Within the region, fruit tree-based agroforestry complements the dominant maize cropping system both in labor requirements and through potential cash generation in the 'hungry season' prior to harvest (Bellow, 2004); however, farmers are currently unlikely to abandon maize production in favor of fruit tree orchards or other crops with fruit trees. Fruit tree-based agroforestry has a higher economic potential, but most maize production is consumed rather than sold. Since shifts in the relative yields of each component occur due to seasonal climatic variability as well as management and establishment densities, additional study of the optimal management regimes acceptable to producers is needed. The value inherent in a production system which better satisfies producers' nutritional needs was not considered in this study, yet may be a large determinant separate from either economic or energetic productivity.

The overall objective of this paper was to determine if incorporation of pear trees into maize farming systems would produce increases in the efficiency of land use, the biological productivity of the systems, or the economic output of the mixed crops. The results clearly confirm these possibilities and thus support the first tenet of the hypothesis that fruit tree-based agroforestry produces benefits by the exploitation of resources that would not be used in tree-less systems (Cannell et al. 1996). Both economic and biological benefits were realized by fruit tree-based agroforestry and further evaluation of this type of system is warranted. It is concluded that fruit tree-based agroforestry produces benefits and that farmers should find fruit tree-based agroforestry an attractive alternative to tree-less cultivation.

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Chapter 9

Biophysical Interactions Between Timber Trees and Arabica Coffee in Suboptimal Conditions of Central America

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Introduction

Especially in the less favorable areas (altitude < 800 m and mean air temperature > 25 °C) that predominate in Central America, there is a renewed interest in managing Arabica coffee (*Coffea arabica* L.) under shade after three decades of promoting intensively managed coffee systems planted in full sun with highly productive dwarf cultivars. The presence of shade trees, especially leguminous species, improves soil fertility (organic matter content and nutrient cycling) and enhances coffee plantation sustainability (Beer et al., 1998; Soto-Pinto et al., 2000). In suboptimal coffee producing areas with low altitude, shade trees greatly reduce excessive solar irradiance and buffer large diurnal variations in air temperature and humidity that are detrimental to coffee physiology (Gutiérrez et al., 1994; Siles and Vaast, 2002). In mountainous areas, associated trees decrease soil erosion and nutrient leaching, especially nitrogen (Babbar and Zak, 1995). Therefore, shade trees play an important role in the Central American region due to the valuable impact of coffee agroforestry (AF) systems on the environment and natural resources such as preservation of biodiversity, soil conservation, water quality, buffering effect around protected areas, reduced pressure on forests, and carbon sequestration (Somarriba et al., 2004). In this region with a long-lasting reputation for commercializing quality coffee, shade can also contribute to the production of high-quality coffee as demonstrated in Guatemala (Guyot et al., 1996), Costa Rica (Muschler, 2001), and Honduras (Decazy et al., 2003). Nonetheless, trees associated to coffee are mainly legume species (*Erythrina* spp. and *Inga* spp.) with no timber values that are pruned periodically to avoid large decreases in coffee production due to competition for light, nutrients and water during the dry period (Beer et al., 1998). Indeed, timber trees are less common in coffee AF systems of Central America despite the fact that timber could greatly help farmers to diversify their income.

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

In 2000, a collaborative research effort was developed to compensate for the persistently low coffee market prices by promoting timber trees in coffee AF systems in Central America (www.casca-project.com) in order to improve coffee farmers incomes through diversification (timber production), production of high-quality coffee, and payment of incentives for environmental services provided by these ecologically sound coffee AF systems.

This study presents results from a 4-year study comparing, under suboptimal conditions (low altitude and hot climate), the effects of two fast-growing timber trees (*Eucalyptus deglupta* and *Terminalia ivorensis*) and a legume tree species (*Erythrina poeppigiana*) on microclimate, coffee (*Coffea arabica* L.) physiology, productivity, and beverage quality.

Materials and Methods

The study was conducted on a 4 ha experimental site on a commercial coffee farm in the southern lowland (altitude of 640 m) of Costa Rica with an annual mean air temperature of 26 °C, annual rainfall of 3500 mm and a pronounced dry season from January until March. Soil was classified as an Ustic Palehumult. The experimental site was established in May–July 1998 with a dwarf coffee cultivar "Costa Rica 95" planted at 1 × 2 m with 3 stems per planting position (14,200 ± 100 coffee stems ha^{-1}) and associated with shade trees, either *E. deglupta* or *T. ivorensis* (planted at 6 × 6 m) or *E. poeppigiana* (planted at 8 × 8 m) positioned within the coffee rows. To simulate a full sun environment, *E. deglupta* trees were removed from units within experimental blocks after eight months of establishment. *Eucalyptus deglupta* and *T. ivorensis* are fast-growing timber tree species well adapted to altitudes below 1200 m with annual rainfall exceeding 1300 mm in Central America. These two tree species are of interest to farmers as they provide shade to coffee plants underneath and produce revenues from timber sales. *Erythrina poeppigiana* is a fast-growing legume tree species originating from the Andean foothills, from Venezuela to Bolivia, and well-adapted to altitudes between 150–1900 m with an annual rainfall between 1000–3000 mm. This legume tree, with no timber or firewood value, is commonly associated with coffee in Central America, especially in Costa Rica, as it provides shade and mulch through periodic pruning, generally twice a year, during the production cycle. The experimental site was intensively fertilized at the rate of three applications per year with nitrogen additions ranging from 55 kg ha^{-1} $year^{-1}$ to 190 kg ha^{-1} $year^{-1}$, potassium addition ranging from 38 kg ha^{-1} $year^{-1}$ to 330 kg ha^{-1} $year^{-1}$, magnesium additions ranging from 11 kg ha^{-1} $year^{-1}$ to 90 kg ha^{-1} $year^{-1}$ and calcium additions ranging from 350 kg ha^{-1} $year^{-1}$ to 850 kg ha^{-1} $year^{-1}$.

The experimental design was composed of four treatments (coffee in full sun and coffee under shade of either *T. ivorensis, E. deglupta* or *E. poeppigiana*) completely randomized in three blocks. Within each block and for each coffee AF system, two experimental units composed of six shade trees and 36 coffee plants were randomly selected. For the timber AF systems, the effect of shade tree proximity to coffee was studied by selecting two coffee plants for each of the five distances to the shade trees (D1: 0.5 m; D2: 1.5 m; D3: 2.08 m; D4: 2.5 m; and D5: 3.2 m). For the full sun and shade with *E. poeppigiana*, 36 coffee plants were randomly selected in each block.

Shade Tree Management, Growth and Light Interception

Low lateral branches of *E. deglupta* and *T. ivorensis*, positioned on the trunk at a height up to 3 m, were removed once a year during the period from 1999 to 2002. All the main branches of *E. poeppigiana* were pruned twice a year to a length of 2 m (as it is generally performed in traditional coffee farming management in Central America). From 2000 to 2003, growth of shade trees was evaluated twice a year by measuring diameter at breast height (DBH in cm), height (H in m), and crown projection (CP in m^2) on a total of 36 trees per species. Light interception by trees was estimated by measuring photosynthetic photon flux density (PPFD in μmol quanta m^{-2} s^{-1}) twice a year with a line quantum sensor (LI-COR, Lincoln, Nebraska, USA) at a height of 1.8 m above the coffee canopy under homogenous sky conditions around noon. In each block, two series of 48 measurements were undertaken at regular and increasing distances from the shade trees. Before and after each series of measurements in the AF plots, PPFD was also recorded in full sun to estimate the percentage of light interception by the tree strata. Shade, provided by *E. poeppigiana*, was not quantified in 2001.

Coffee Growth and Production

In May of 2000, 2001, and 2002, coffee stem basal diameter at 35 cm above the soil surface was measured as an indication of coffee adaptation to the microclimatic conditions provided by the different sun and shade treatments. Coffee leaf area was also estimated by measuring individual area of all the leaves on seven branches distributed at regular intervals within the coffee canopy. From January to March 2002, flowering was registered on these seven selected branches. Production of coffee berries was recorded for the 2001 production cycle and estimated from berry load present a month before beginning of harvest for the 2000 and 2002 production cycles.

Coffee Photosynthesis

In 2001, six coffee plants were selected in each experimental unit to monitor net photosynthesis (Pn), stomatal conductance (gs), PPFD, and temperature at the leaf level with a differential CO_2/H_2O infrared gas analyzer ADC-LCA4 (ADC BioScientific Ltd., Hoddesdon, UK). The measurements were performed on twelve leaves distributed at four levels within the coffee canopy, during three periods of the day (7:00 a.m. to 9:00 a.m.; 11:00 a.m. to 1:00 p.m.; and 3:00 p.m. to 5:00 p.m.) over 10 days during 3 months (February, May, and July). In the ecological conditions of this site, February is representative of the dry period with low vegetative growth and an absence of coffee berries. May is representative of the transition period at the beginning of the rainy season with a marked vegetative flush after flowering. July is representative of the rainy season with a high carbohydrate demand from berries at the beginning of the bean filling stage.

Coffee Transpiration

From December 2001 to July 2002, sap flow of eight coffee plants (two plants per system) was monitored during five consecutive days per month with stem-flow sensors (Dynamax Inc., Houston, Texas) on the main orthotropic stem of plants with 3½ to 4 years of age. Foliar area of each monitored stem was recorded to estimate daily transpiration on a leaf area basis. To estimate the daily coffee transpiration per hectare (in mm day^{-1}), the average coffee transpiration of the two coffee stems monitored was multiplied by the total basal stem area per hectare for each system.

Coffee Bean Size and Composition and Beverage Quality

These attributes were assessed on one composite sample of fully ripe coffee berries taken from each of the six experimental units per coffee system during the peak harvest for the 2001 and 2002 production cycles. Coffee samples were prepared by the traditional wet processing method (wet de-pulping, anaerobic fermentation for 24 h, sun-drying, and de-husking) to obtain ready to be roasted coffee beans (commonly named green beans). Bean size was assessed with a series of sieves after sun drying to a water content of 12%. Percentage of green beans with larger sizes (bean diameter > 6.75 mm) was calculated. A 50 g sample of green beans was analyzed for caffeine, trigonelline, chlorogenic acids, and fat content by near infrared reflectance spectrometry (NIRS) based on calibration curves established for each compound (Guyot et al., 1993). These compounds are considered important precursors for coffee aroma and organoleptic properties of beverage upon degradation during roasting through the Maillard reaction (Dart and Nursten, 1985). These analyses were performed on a NIRS model 6500 (NIRS System Inc., Silver spring, MD) based on reflectance of ground green coffee (grinding <0.5 mm). The NIRS system was driven by NIRS2 (4.0) software (Intrasoft Intl., Port Matilda, PA). After eliminating defective beans, 150 g samples of green beans were roasted for 7–8 min at 220 °C in a laboratory-roaster, Probat, type BRZ2 (D-46427, Emmerich, Germany). Cup quality tests were assessed on an infusion prepared with 12 g of roasted and ground coffee. A panel of 10 persons tasted three cups of 120 ml of infusion for each sample. The main beverage attributes (acidity, bitterness, astringency, and body) were estimated using scales ranging from 0 to 5, where 0 = nil, 1 = very light, 2 = light, 3 = regular, 4 = strong, and 5 = very strong. An additional preference score was used ranging from 0 to 4, where 0 = not good for drinking, 1 = bad, 2 = regular, 3 = good, and 4 = very good. The tests were repeated three times and values presented in this report are means of three sessions.

Data Analysis

SAS (Statistical Analysis System, V8) software was used to perform all statistical analyses. Mean values were compared with the Newman and Keuls test at a significance level of 5%.

Results

Tree Growth and Microclimate Characteristics

A significantly faster growth was observed for *T. ivorensis* compared to that for *E. deglupta* during the 4 years after plantation establishment, especially in terms of crown projection (Table 9.1). Crowns of *T. ivorensis* started overlapping each others before 2.5 years of age whereas crown overlapping of *E. deglupta* did not happen before 38 months. Due to its broad leaves and larger crown, *T. ivorensis* provided a denser shade than *E. deglupta* during the rainy season, especially in 2001 and 2002 (Figure 9.1). During the rainy season, the canopy of *T. ivorensis* intercepted up to 60% of PPFD while *E. deglupta* only intercepted around 30–40%. However, *T. ivorensis* shed more heavily its leaves than *E. deglupta* during the dry season which resulted in a lower but more constant shade level during the whole year for coffee under *E. deglupta*. PPFD interception by *E. poeppigiana* was in the low range of 0–25% during the dry season and 20–40% in the wet season. Air temperature

Table 9.1 Vegetative growth (diameter at the breast height: DBH; trunk height: H; and crown projection: CP) of shade trees (*Eucalyptus deglupta, Terminalia ivorensis*, and *Erythrina poeppigiana*) at 22 months (2000), 34 months (2001), and 44 months (2002) after transplanting

	2000			2001			2002		
	DBH (cm)	H (m)	CP (m^2)	DBH (cm)	H (m)	CP (m^2)	DBH (cm)	H (m)	CP (m^2)
Eucalyptus	5.2 a[a]	4.6 a	4.7 a	9.0 a	7.8 a	20 a	11.3 a	9.7 b	33 a
Terminalia	7.7 b	4.8 a	11.5 b	13.7 b	8.5 a	38 b	16.8 b	9.5 b	44 b
Erythrina[b]	nd[c]	nd	nd	nd	nd	nd	18.3 b	5.2 a	27 a

[a] Mean values (n = 12) within a column with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P = 0.05$).

[b] Crown branches heavily pruned twice a year.

[c] Not determined experimentally.

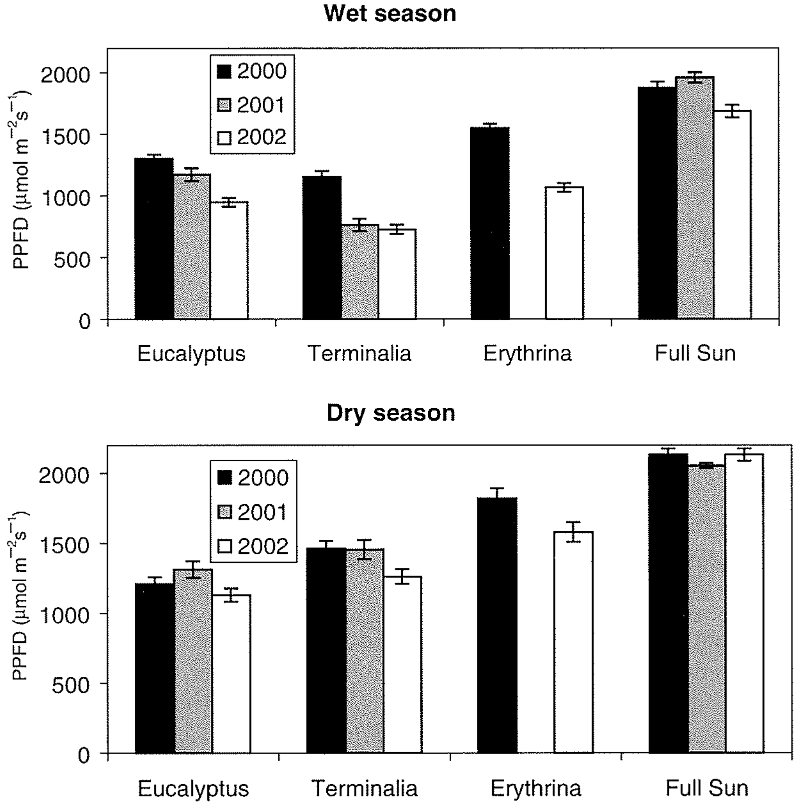

Figure 9.1 Light availability (PPFD in µmol m^{-2} s^{-1}) for coffee plants under shade trees (coffee under *Eucalyptus deglupta* or *Terminalia ivorensis* or *Erythrina poeppigiana*) in comparison to full sun during the wet and dry seasons of the 2000–2002 production cycles, except for *Erythrina poeppigiana* in 2001

around coffee leaves was significantly affected by tree shade as illustrated by the values registered at three periods during the day below the timber trees and in full sun during the rainy season of 2001 (Figure 9.2). Air temperature was 2–4 °C lower under shade of timber trees than in full sun, especially from morning to midday.

Effects of Shade on Coffee Growth and Production

Two years after planting, the distance of coffee to the shade tree had a significantly negative effect on coffee growth and production under *T. ivorensis* but none under *E. deglupta* (data not shown). Coffee plants at the closest distances (D1: 0.5 m and D2: 1.5 m) from *T. ivorensis* grew and produced significantly less than the ones at larger distances (D3: 2.08 m; D4: 2.5 m; and D5: 3.2 m). Four years after planting, no significant effect of the proximity of the shade tree to the coffee plant was observed as shade was more homogeneously distributed over the whole experimental plots. Under the suboptimal conditions of this site, coffee growth and production was increased by shade after the initial establishment phase. The lighter and more uniform shade provided by *E. deglupta* during the year resulted in the highest production (Table 9.2). The denser shade provided by *T. ivorensis* resulted in the highest coffee vegetative growth but decreased production as compared with that of coffee under *E. deglupta*. Due to heavy pruning, the lower and irregular shade provided by *E. poeppigiana* did not significantly improve coffee production as compared with that of coffee in full sun. Cumulative coffee production over the three monitored cycles was 16% and 49% lower in full sun than under *T. ivorensis* and *E. deglupta*, respectively. For the two cycles, where production was monitored, cumulative coffee production under *E. poeppigiana* was 26% and 59% lower than that under *T. ivorensis* and *E. deglupta*, respectively. Shade increased the length of berry bearing branches, the number of productive nodes per branch and the area of individual leaf (Table 9.3), as well as the total branch leaf area (data not shown). Shade decreased flowering intensity, but still resulted in a higher final berry load per productive node and branch due to the lower berry drop registered during the production cycle under timber trees (Table 9.3).

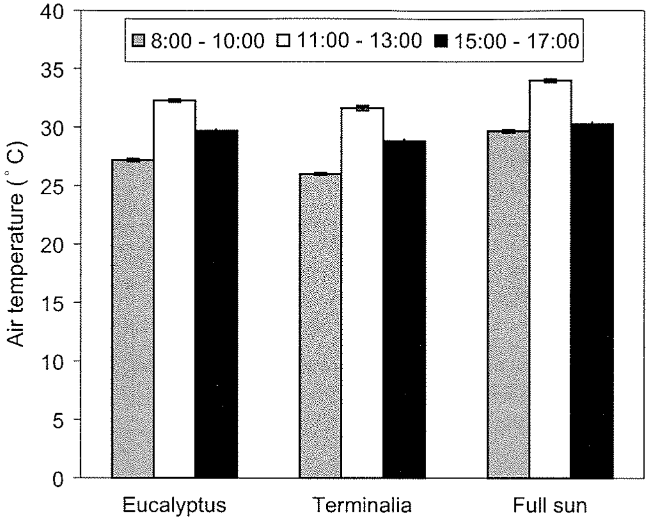

Figure 9.2 Air temperature around coffee leaves under shade timber trees (*Eucalyptus deglupta* or *Terminalia ivorensis*) in comparison to full sun during the wet season of the 2001 production cycle

Table 9.2 Effects of management systems (coffee in full sun and coffee under *Eucalyptus deglupta, Terminalia ivorensis* or *Erythrina poeppigiana*) on coffee vegetative growth (stem basal area per hectare: SBA and coffee leaf area index: LAI) and production of green beans (Prod) over three consecutive production cycles

	2000			2001			2002		
Coffee Under	SBA (m^2 ha^{-1})	LAI (m^2 m^{-2})	Prod (kg ha^{-1})	SBA (m^2 ha^{-1})	LAI (m^2 m^{-2})	Prod (kg ha^{-1})	SBA (m^2 ha^{-1})	LAI (m^2 m^{-2})	Prod (kg ha^{-1})
Full sun	5.88 b[a]	1.43 a	740 a	6.38 b	1.21 c	350 b	6.91 b	1.04 b	700 c
Eucalyptus	6.02 a	0.94 c	620 b	6.63 b	1.52 b	1013 a	8.16 a	2.23 a	1890 a
Terminalia	5.40 c	1.15 b	510 b	7.17 a	1.91 a	449 b	9.02 a	2.78 a	1160 b
Erythrina	nd[b]	nd	nd	nd	nd	380 b	8.04 a	1.83 ab	814 c

[a] Mean values (n=36) within a column with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P=0.05$).

[b] Not determined experimentally.

Table 9.3 Effects of shade management (coffee in full sun and coffee under *Eucalyptus deglupta, Terminalia ivorensis* or *Erythrina poeppigiana*) on vegetative and productive characteristics of coffee plants during the third production cycle (2002)

Coffee under	Full sun	Eucalyptus	Terminalia	Erythrina
Branch length (cm)	40 b[a]	58 a	60 a	46 b
Individual leaf area (cm^2)	17 c	36 b	45 a	30 b
Productive nodes per branch	6.7 b	9.0 a	7.5 b	7.4 b
Flowers per node	10.9 a	9.5 b	9.7 b	9.5 b
Leaf berry ratio (cm^2 $fruit^{-1}$)	6 c	11 b	16 a	11 b
Berry drop (%)[b]	43 a	20 c	17 c	34 b
Final berry load per node[b]	6.2 b	7.6 a	8.0 a	6.3 b

[a] Mean values within a line with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P = 0.05$).

[b] 26 weeks after flowering initiation and four weeks before harvest.

Effects of Shade on Coffee Physiology

During the rainy season, coffee leaves reached their highest gs (data not shown) and Pn (Figure 9.3) rates in the morning hours and decreased thereafter due to increasing air temperature around coffee leaves (Figure 9.2). Lower Pn rates were registered under the densest shade of *T. ivorensis* at all periods of the day in comparison to that under shade of *E. deglupta* or in full sun (Figure 9.3). With the exception of 2 months (January and June), transpiration rates monitored via sap flow measurements demonstrated that coffee in full sun transpired more on a leaf area basis than under shade of timber trees (Table 9.4) due to exposition of the sun-grown coffee plants to higher solar radiation (Figure 9.1) and air temperature (Figure 9.2). However, coffee transpiration per hectare was generally higher under shade of *E. deglupta* than in full sun (data not shown) due to higher vegetative growth of the coffee trees in shade (Table 9.2). Despite higher vegetative growth, coffee transpiration per hectare under shade of *T. ivorensis* was generally not different than that in full sun due to low solar radiation received by the coffee plants under the dense

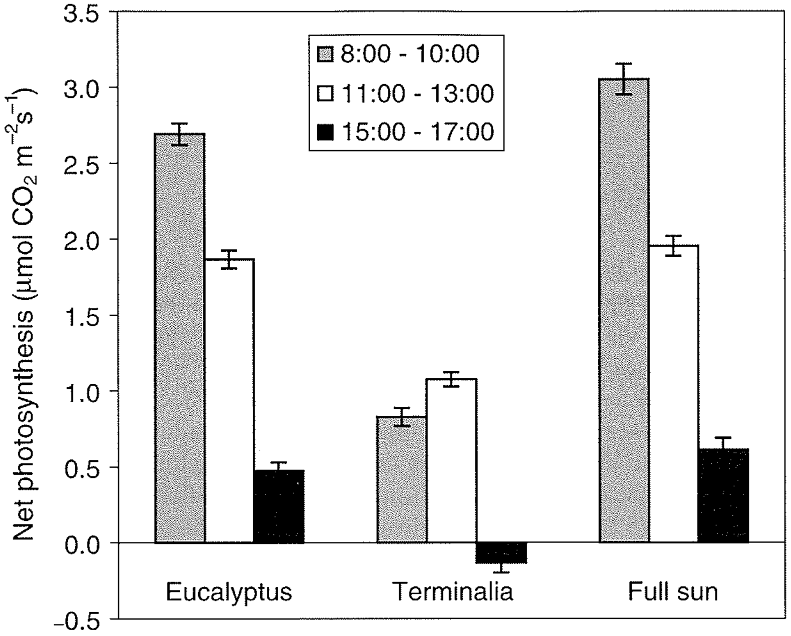

Figure 9.3 Net photosynthesis of coffee leaves under shade trees (*Eucalyptus deglupta* or *Terminalia ivorensis*) in comparison to full sun at three periods along the day during the wet season of the 2001 production cycle

Table 9.4 Effects of shade management (coffee in full sun and coffee under *Eucalyptus deglupta, Terminalia ivorensis* or *Erythrina poeppigiana*) on coffee daily transpiration (l day^{-1} m^{-2} of foliar area)

Coffee under	Full sun	Eucalyptus	Terminalia	Erythrina
December	0.83 a[a]	0.62 b	0.47 b	0.58 b
January	0.78 a	0.80 a	0.57 b	0.98 a
February	0.87 ab	0.39 b	0.45 b	1.06 a
March	1.04 a	0.54 b	0.56 b	0.61 b
April	1.59 a	0.86 b	0.74 b	1.74 a
May	0.80 a	0.57 b	0.49 b	0.68 b
June	0.72 a	0.60 a	0.38 b	0.74 a
July	0.79 ab	0.63 ab	0.39 b	1.01 a

[a] Values within a line with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P = 0.05$).

shade of this tree species (Figure 9.1). Coffee transpiration was particularly high under *E. poeppigiana* during the dry season when this species was shedding most of its leaves and coffee plants were exposed to high solar radiation (Figure 9.1).

Effects of Shade on Coffee Quality

Shade significantly affected coffee berry ripening. In a warmer micro-environment due to higher solar radiation, coffee berry flesh ripened faster in full sun than under shade. Therefore, the harvest peak was delayed by about 6 weeks due to shade, especially under the denser shade of timber trees. During the 2001 production cycle and by the second harvest (mid-November), more than 95% of the coffee berries were already harvested in full sun compared to 80% under the low shade of *E. poeppigiana* and less than 55% under the shade of timber trees. During the 2002 production cycle, the observations confirmed this delaying effect of shade on coffee berry ripening as 75% of berries were already harvested at the second harvest in full sun or low shade of *E. poeppigiana* while less than 45% were harvested under the shade of timber trees. This longer period of maturation under shade, and hence better bean filling, resulted in significantly higher percentages of coffee beans with larger sizes (bean diameter > 6.75 mm) during the two consecutive production cycles monitored (Table 9.5). Shade had also a significant effect on the biochemical composition of coffee beans (Table 9.5). In 2001, caffeine and fat content were higher in beans of shade-grown plants whereas chlorogenic acids and trigonelline content were higher in beans of sun-grown plants. In 2002, the same significant effects of shade could be observed except for chlorogenic acids. Shade significantly affected beverage quality (Table 9.6). Negative attributes, such as bitterness and astringency, were higher for coffee beverage prepared from sun-grown beans that from shade-grown ones during the two monitored production cycles. Furthermore, positive attributes such as beverage acidity and preference were significantly higher for coffee produced under the shade of timber trees (Table 9.6).

Table 9.5 Effects of shade management (coffee in full sun and coffee under *Eucalyptus deglupta, Terminalia ivorensis* or *Erythrina poeppigiana*) and year of production on percentage of beans with larger sizes and bean biochemical composition (in g kg^{-1} of bean dry weight)

	Large beans (%)		Caffeine (g kg^{-1})		Fat (g kg^{-1})		Chlorogenic acid (g kg^{-1})		Trigonelline (g kg^{-1})	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Sun	67 b[a]	56 b	14.2 b	13.6 b	132 b	125 b	77.1 a	82.6 a	10.7 a	10.1 a
Eucalyptus	72 a	67 a	14.8 a	14.1 a	141 a	130 a	76.2 b	82.1 a	9.9 b	9.7 b
Terminalia	72 a	67 a	14.8 a	14.1 a	141 a	133 a	76.6 b	82.3 a	10.0 b	9.7 b
Erythrina	69 b	62 a	14.5 b	13.7 b	137 ab	122 b	77.0 a	82.2 a	10.5 a	9.9 a

[a] Values within a column with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P = 0.05$).

Table 9.6 Effects of shade management (coffee in full sun and coffee under *Eucalyptus deglupta, Terminalia ivorensis* or *Erythrina poeppigiana*) and year of production on beverage characteristics

	Acidity[a]		Bitterness		Astringency		Body		Preference[b]	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Sun	1.67 b[c]	2.21 b	1.95 a	1.88 a	0.86 a	0.51 a	2.91 a	2.67 a	2.19 c	2.28 b
Eucalyptus	2.27 a	2.45 a	1.65 b	1.65 b	0.68 c	0.35 b	2.78 b	2.50 a	2.70 b	2.80 a
Terminalia	2.13 a	2.41 a	1.75 b	1.73 b	0.70 c	0.36 b	2.89 b	2.53 a	2.90 a	2.78 a
Erythrina	1.91 ab	2.27 b	1.86 a	1.75 b	0.79 b	0.34 b	2.72 b	2.66 a	2.32 c	2.36 b

[a] Scores for acidity, bitterness, astringency, and body were based on a scale of 0–5.

[b] Overall preference was based on a scale of 0–4.

[c] Mean scores (from 10 judges during 3 tasting sessions) within a column with the same letter(s) do not differ significantly according to the test of Newman-Keuls ($P=0.05$).

Discussion and Conclusions

These results show that shade provided by *T. ivorensis* had a negative impact on coffee growth and production, but only limited to the initial phase of plantation establishment due to the particularly large crown projection of this tree species when it is not recommended to prune the lower lateral branches. On the medium term, shade of both timber trees improved coffee growth and increased productivity under the present hot and suboptimal ecological conditions that are quite common in many coffee producing regions of Central America. These results confirm previous studies showing that artificial shade (Muschler, 2001; Vaast et al., 2002) or shade trees (Beer et al., 1998) reduce coffee fruit load per productive node through a lower flower induction. However, they demonstrate that, in these suboptimal conditions, coffee under shade still produces more than in full sun due to a lower berry drop during the production cycle and a larger bean size at harvest. These beneficial effects of shade are due to higher vegetative growth and higher leaf to berry ratios of shade-grown coffee plants which results in a higher carbohydrate supply to berries, especially during the period of bean filling (Vaast et al., 2002). With a coffee production enhanced by almost 50% over three consecutive production cycles, *E. deglupta* is a better shade species than *T. ivorensis* as it provided a more constant and lower shade level (20–40%) along the year. The denser shade (60%) of *T. amazonia* during the rainy season increased coffee growth but reduced coffee productivity without alleviating further the suboptimal conditions of this experimental site characterized by high air temperature above the optimal range (20–25 °C) for Arabica coffee photosynthesis (Mosquera et al., 1999; Siles and Vaast, 2002). Strong pruning of *E. poeppigiana* twice a year is very common in the medium to high altitudinal range (800–1200 m) in Central America. At the low altitude (< 650 m) of this experimental site, this traditional practice resulted in better coffee performance than in full sun but a lower one than with either timber species. Nonetheless, it should not be inferred from the present results that *E. poeppigiana* is a less suitable shade species for coffee cultivation than timber tree species in lowland conditions. A less frequent and lighter pruning could have certainly improved the beneficial impact of this legume species not only in terms of light interception and microclimatic conditions but also with respect to soil fertility. The fertilization regime was very high in the present experimental site and consequently soil nutrients were not limiting for coffee and tree growth. Therefore, a higher positive impact of *E. poeppigiana* could be expected with lower fertilizer inputs and a lighter pruning regime through the contribution of nutrient-rich mulch, particularly nitrogen via N_2-fixing capacity of this legume. Indeed, heavy and frequent pruning has a strong depressive effect on root and nodule turnover and hence N_2-fixing capacity of *E. poeppigiana* (Nygren and Ramirez, 1995). The seasonal phenological differences between shade species, especially foliage shedding and renewal, had also important impacts on coffee. The rapid and complete loss of leaves of *E. poeppigiana* during the dry season was detrimental to coffee when the buffering effect of shade is greatly needed to ensure an improved protection to coffee against solar radiation and heat stress as indicated by the high coffee transpiration under this legume shade species during the months of January and February. This highlights the fact that management practices (selection of the shade tree species, planting density, tree thinning, and frequency of canopy pruning) must be adapted to local ecological conditions to ensure that the level of shade is neither too high for adequate coffee growth and productivity nor too low for effective protection of coffee plants against adverse climatic conditions.

Clearly, the present beneficial effects of timber trees on coffee growth and productivity under suboptimal conditions need to be confirmed over a longer time period. Recent farm surveys on coffee management systems indicate that the monitored timber tree species (*E. deglupta* and *T. ivorensis*) and several other ones commonly encountered in the coffee fields, such as *Cordia alliodora* and *Terminalia amazonia*, are highly compatible with an acceptable coffee production that is far higher than the average world productivity of 300–500 kg of green beans per hectare. More importantly, these timber species provide additional revenues from sales of timber that could account for more than 50% of that regenerated by cumulative coffee production over 15 years (Dzib, 2003). Incidentally, *T. amazonia*, an indigenous timber species of Latin America, appears to be preferred over *T. ivorensis* by coffee producers in Central America. Especially in Costa Rica, many producers have started over the last decade to associate this indigenous species in their coffee fields due to a more compact crown than that of *T. amazonia* and a comparable wood quality. Indeed, productive performance of associated trees and especially wood quality need to be considered as revenues derived from sales of timber can greatly help farmers to diversify their income in times of world overproduction characterized by low coffee prices. Although *C. alliodora, T. amazonia* and *T. ivorensis* produce lower biomass than *E. deglupta*, their high quality wood is far more appreciated than that of the latter by the local industry and is paid 50–100% more to farmers (Dzib, 2003).

The present results confirmed the importance of shade on bean biochemical composition and quality of the coffee beverage (Guyot et al., 1996; Muschler, 2001; Decazy et al., 2003; Vaast et al., 2006). By decreasing air temperature by several degrees and lowering coffee berry exposure to solar radiation, shade lengthened, by up to six weeks, the ripening of coffee berry flesh and allowed extra time for a more complete bean filling. This shade effect has been proposed as one of the main reasons explaining differences in beverage quality between shade and sun-grown coffee (Guyot et al., 1996). In the present study, trigonelline content was higher in beans of sun-grown plants than in that of shade-grown ones. This indicates that bean maturation was not completed and explains the higher bitterness and astringency of the beverage of sun-grown coffee. These results demonstrate that adequate management of shade trees in coffee plantation can result in the production of high quality in low-altitude coffee producing zones that predominate in Central America. This is an important aspect to consider in order to maintain the reputation of high quality of the coffee produced by Central American countries, increase the sustainability of these coffee plantations and ensure the economic viability of coffee farms through schemes rewarding quality as some have been initiated over the last few years by cooperatives and private coffee buyers.

From the present results, it can be concluded that coffee agroforestry based on timber tree species appears to be an ecologically and economically viable option in Central America as it should improve farmers' revenues and compensate the current low coffee prices through diversification (sale of timber) and commercialization of high quality coffee. Furthermore, payments for environmental services (soil conservation, water quality, buffering effect around protected areas, reduced pressure on forests, preservation of biodiversity and carbon sequestration) provided by these coffee agroforestry systems could also contribute to enhance their economical sustainability in the future via public, private and international schemes.

Clearly, more research is needed to screen additional indigenous or introduced species that have desirable canopy and wood characteristics. Research is also worth undertaking on shade strata composed of multiple tree species to insure a more constant level of shade during the whole production cycle and to enhance environmental services, particularly biodiversity conservation.

Acknowledgments The authors thank the commercial farm of Verde Vigor SA. for the maintenance of the experimental plot, Jean-Jacques Perriot, Bernard Guyot, Fabrice Davrieux and Fabienne Ribeyre, researchers of the CIRAD laboratory of coffee technology, for the NIRS and cup quality analyses, the European Commission (INCO project CASCA, ICA4-CT-2001-10071, www.casca-project.com) and the Science and Cultural Cooperation Centre of the French Embassy in Costa Rica for supporting part of the operational costs of this research.

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Section 3

Resource Allocation in Agroforestry Systems: Belowground Processes

Chapter 10
Agroforestry Management Effects on Plant Productivity Vectors within a Humid–Temperate Hardwood Alley-cropping System

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Introduction

Economic analyses have shown that combining hardwood trees and agricultural crops into alley-cropping systems has the potential to increase the profitability of plantation forestry in the humid temperate midwestern USA (Williams and Gordon, 1992; Benjamin et al. 2000). Traditionally in this region, trees and agronomic crops are grown separately in monocultural systems. Management prescriptions for the combined systems (reviewed by Gordon and Newman, 1997) are still being evaluated because most established agroforestry systems in the region are only 10–30 years old (40–80 years of tree growth required between tree harvests for timber and veneer production).

In order to increase understanding of the biological potential of these systems, management effects on tree- and crop productivity can be explored by monitoring changes in plant productivity vectors over short-term intervals (e.g. daily, monthly, or yearly time steps). Plant productivity vectors include a magnitude (e.g. soil water content, photosynthetically active radiation, nutrients in soil solution) and direction (e.g. tree or crop uptake, soil stabilization, transformation, leaching loss) and changes in these components will be early indicators of the impact of management choices.

An extensive data set concerning hardwood alley-cropping systems is from Purdue University's Southeast Purdue Agricultural Center (SEPAC) research station located in southern Indiana (Butlerville, IN, USA) (Gillespie et al. 2000). Evidence for black walnut tree effects on alley resource levels at this site were obtained from measurements of soil water, soil and vegetation N, and photosynthetically active radiation (0.4–0.7 µm) (Gillespie et al. 2000; Jose et al. 2000a,b). The potential for juglone toxicity on these sites has also been investigated (Jose and Gillespie, 1998a, b; von Kiparski, 2005), but is not reported here. From system establishment (year 1 = 1985) until year 12 (1996) after establishment, the productivity of maize (C4 carbon assimilation pathway) planted in the alleys of this black walnut alley-cropping system

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

(alley width = 8.5 m) declined, which indicated increased crop interaction with the hardwood trees and the need to switch to more tolerant alley crops (e.g. with C3 carbon assimilation pathway). Research at the SEPAC black walnut alley-cropping system in year 11 and year 12 after system establishment focused on ascribing the observed alley maize yield declines to either belowground (e.g. water, nutrients, phytotoxicity) or aboveground (e.g. light) tree–crop interactions by separating maize and walnut tree roots using soil trenching (trench) with (barrier) and without (control) plastic-barrier insertion. Maize grain yield decline in the agroforestry system was attributed to belowground resource limitation, and aboveground resource (i.e. light) limitation from tree shading only had a secondary role (Gillespie et al. 2000).

The objective of this study was to determine agroforestry management effects on alley-cropping system productivity (tree and crop) over time and on changing aboveground (i.e. light) and belowground (i.e. fertilizer N, soil water, and labile organic N) resource productivity vectors for a humid, temperate hardwood alley-cropping system. Existing data from the site collected in year 1–11 since establishment (year 1 = 1985) (Gillespie et al. 2000; Jose et al. 2000a,b) and additional data collected in years 16–18 since establishment were evaluated with respect to biological and ecological outcomes.

Materials and Methods

Site and Agroforestry System Description

The study site is located in southeastern Indiana, USA at the Purdue University research farm (SEPAC, Butlerville, IN) (39°03′N, 85°30′W). The site's soil was previously characterized as a Parke soil (Gillespie et al. 2000) but has been reclassified to account for an incipient fragipan within the B horizon, and it is tentatively described as a Ryker series (fine silty, mesic Fragaquic Paleudult) intergrading to a Cincinnati series (D. Marshall, USDA Soil Scientist, 2004, USDA, personal communication).

The alley-cropping system consists of black walnut trees positioned in three parallel north–south rows, each 118 m in length and spaced 8.5 m apart to form two parallel alleys for cropping. This arrangement of three rows of trees forming two alleys was repeated at four different locations (blocks), creating a total walnut tree planting area of 0.92 ha. The tree management objective is to maximize veneer quality wood production as part of an alley-cropping system. In the mid-summer of year 17, the canopy of 15 randomly selected trees had a mean crown depth (measured from top of bole to the top of the crown) of 7.0 m and mean crown coverage area of 24.9 m^2. The mean tree height was 7.42 m in year 11 and 12.7 m in year 17. In most years, six rows of maize were planted within the cropping alleys which is described in detail by Gillespie et al. (2000).

Meteorological and Soil Water Measurements

Mean air temperature, precipitation, reference evapotranspiration (ET_o), and incident-solar radiation were characterized for the study site using an on-farm weather station in order to examine patterns of water stress potentially impacting agroforestry yields. The FAO Penman-Monteith equation was used as the method for determining ET_o and provides a standard to which reference evapotranspiration at different periods can be compared (Allen et al. 1998; Allen, 2000). Photosynthetically active radiation (PAR; 400–700 nm) above the black walnut trees of the alley-cropping system was measured in all years, but for the alleys it was measured only in year 11, year 16, and year 17 (year 1 = 1985). PAR was determined with either a ceptometer (model SF-80; Decagon Devices, Pullman, WA, USA) in year 16 or with daily integration of quantum light sensors (model QA-190, LICOR Corp., Lincoln, NE, USA) in year 11 and year 17. Percent PAR transmittance was calculated as the ratio of below- to above-canopy PAR. The soil volumetric water contents within maize rows (row 1 and row 3) were determined biweekly during the growing season in year 12 (year 1 = 1985) (Jose et al, 2000a) and year 16 using a Troxler neutron moisture gauge (model 3330, Troxler Electronics, Inc. NC, USA). A water content reflectometer (model CS-615, Campbell Scientific, Logan, UT, USA) provided similar information for year 17. The maize cropping row was instrumented for soil moisture determination because this is where > 60% of incoming precipitation is redirected (Dolan et al. 2001) and the location of greatest maize root biomass and potential depletion of water and nutrients.

Soil Nitrogen and Carbon Pools

Sampling of soil solution for inorganic nitrogen determination in year 16 was performed using tension lysimetry beneath the effective rooting zone. Since tree and crop roots were not found below the 90-cm soil depth in year 16, nitrogen in soil solution at the 90-cm soil depth was considered unavailable to plants, having passed through the rooting zone. Soil solution was sampled using ceramic-tipped porous-cup lysimeters (model 1900, Soil Moisture Equipment Corp., Goleta, CA, USA) installed in row 1 (alley edge) and row 3 (mid alley) across treatment locations at the 90-cm soil depth 1 year prior to commencing measurements. Six lysimeters were installed per experimental plot. These soil solution samplers have air entry values of –0.10 MPa, and only sampled when soil water levels were greater than –0.07 MPa. A pressure of –0.07 MPa was placed on each porous-cup sampler using a hand vacuum pump one day prior to soil solution collection. Soil solution in the porous-cup lysimeters was sampled at 7- to 14-day intervals across the growing season. Drought conditions precluded soil solution collections on some dates and plots in the late summer.

Uptake of fertilizer N by maize in the black walnut agroforestry system was assessed by application of granular ^{15}N-enriched (5.5 atom%^{15}N) $(NH_4)_2SO_4$ fertilizer (Isotec, Sigma-Aldrich) to microplots (2.5×0.76m) in each experimental plot, including one in row 1 (alley edge) and one in row 3 (mid alley), at addition rates corresponding to amounts of unlabeled N applied to the adjacent alley areas (200kg N ha^{-1} in year 16). This followed the methodology of Jose et al. (2000b) on the same site in year 12 (microplot overlap between years was avoided). The labeled-fertilizer materials were applied to the microplots in year 16 on April 27 and were followed by (1) determination of the ^{15}N tracer enrichment of soil solutions at the 90-cm depth in the plots across the growing season to trace fertilizer N; (2) detection of labeled-^{15}N uptake by maize grain and stover at harvest.

In early May of year 18 after agroforestry establishment (year 1 = 1985), spatial patterns of labile organic N (Mulvaney et al. 2001) pools across the alley-cropping system were investigated in order to discover any tree effects on this readily available soil N fraction. Soils were sampled and analyzed from the depth intervals: 0–15, 15–30, 30–60 and 60–90cm at the alley edge (row 1) and the mid alley (row 3). In addition, an adjacent agronomic field planted in maize–soybean rotation was sampled to provide land-use comparison with a system without trees. Soils were sampled using a 2-cm diameter stainless steel push rod obtaining five to six cores per plot, which were composited into a single sample for analysis. A similar sampling scheme was utilized in year 16 to measure soil carbon and soil N content in the tree row and row 3 (mid alley) for each plot. Soil samples were air-dried and sieved to pass through 2-mm mesh prior to chemical analysis.

Design Structure, Randomization, and Statistical Analyses

Tree root pruning was conducted in year 11 as part of the experiment described by Gillespie et al (2000). Briefly, a single-factor randomized complete block experiment was established in year 11 (1995) involving tree root manipulation (tree root barrier installed after trenching, trenching only, control with no tree root manipulation) to investigate belowground versus aboveground plant interactions. The two root cutting treatments (barrier and trench) (fixed effects) along with the control were assigned within each agroforestry block using separate and independent randomizations. The experimental unit for each treatment consisted of three rows of trees with two alleys and measured 17m wide x 33.3m long. The root cutting treatments were applied to all three-tree rows within each experimental unit resulting in two alleys per treatment per block.

Additional treatment factors explored as part of designed experiments to investigate spatial and temporal variation in tree and crop production and productivity vectors on the site included production year, distance from the tree row, and soil depth interval. For discussion purposes, years investigated were designated as years since establishment (1985 = year 1; 1986 = year 2; etc.). For crop production data, only years in which maize was planted in the cropping alleys were investigated. For tree production, the period from year 8 until year 17 since establishment was analyzed. Two of the six alley maize cropping rows were investigated and labeled as row 1 (the first maize row from west to east and adjacent to the tree row at the alley edge) and row 3 (the third row from west to east and situated at the proximate mid-alley position). Soil depth intervals examined varied depending upon the response variable investigated.

When analyzing black walnut tree diameter and diameter growth within the randomized complete block design, the experimental units were portioned into a second experimental unit (split block) representing year (fixed effect), if no tree removals occurred across a year grouping (i.e. during years 11–14). These conditions made it possible to compare treatment effects across years without risk of confounding statistical interpretations with effects related to tree removal. Individual black walnut trees, on which diameter measurements were taken, were considered random effects nested within the treatment *x* block experimental unit. The observational units were the individual trees within the experimental unit. Tree row (1–3) was also investigated as a split-block effect on tree diameter and diameter growth.

Maize yields, black walnut tree root biomass, soil water content, soil solution N, soil labile organic N, soil C, and soil N content were interpreted using the same randomized complete block root-barrier experiment (barrier versus control only, not trench) as described above but with the addition of a distance (maize row 1 and row 3) effect and soil depth effect. Interaction terms were investigated for significance ($P<0.05$) prior to exploring main effects.

A tree-branch pruning effect could not be statistically interpreted since it was applied to all trees on the site and year-to-year comparisons were confounded with system development and annual climate variations.

Transformation of data was performed if violations of the assumptions of the particular statistical test were significant ($P<0.05$). Analyses of variance (ANOVA) for treatment effects within the randomized complete block root separation experiment were performed using PROC MIXED (Littell et al. 1996) of the SAS system (release 802 SAS Inst Cary NC USA). The LSMEANS statement was used for examining differences among means corresponding to levels of the treatments. The SLICE option of the LSMEANS statement was used to simultaneously test for differences among levels of one factor within levels of a second factor when an interaction term was significant and to minimize the inflation of Type I error rates while maintaining a relatively high level of power in the test. Differences among means were considered significant with $P < 005$ unless otherwise specified.

Chemical Analyses of Vegetation, Soil, and Soil Solution Samples

The carbon and nitrogen content of maize grain, maize stover, and soils from the black walnut alley-cropping system were measured using a Leco CNS 2000 analyzer (Leco Corp., St. Josephs, MI, USA) after oven-drying samples at 65°C and grinding the materials to a fine powder using a ball mill (Retch, Haan, Germany).

All vegetation tissue was sampled from experimental plots according to the procedures described by Gillespie et al. (2000).

Nitrogen ^{15}N isotope analysis was performed on maize Kjeldahl digests and soil solution samples according to the sample preparation and analytical diffusion methodology of Khan et al. (1997). The University of Illinois ^{15}N Analysis Service (Urbana, IL) analyzed the prepared diffused samples for ^{15}N enrichment. Inorganic nitrogen determinations on unlabeled materials, including 2 M KCl soil extracts (1:5 m/v) and soil solution samples were made again using the diffusion methods of Khan et al. (1997).

Labile organic nitrogen (amino sugar N) was determined using the Illinois Soil N Test (Khan et al. 2001; Mulvaney et al. 2001). This test has been successful in detecting fertilizer requirements for maize production (Mulvaney et al. 2001), and was selected to reveal tree effects on labile organic N pools important for crops grown in the alley.

Results and Discussion

Agroforestry Management Effects on Tree and Alley Productivity

The tree root separation treatments (barrier and trench), imposed in the spring of year 11, had an immediate effect on tree diameter growth, with significant ($P<0.05$) reductions in annual tree growth with respect to the control (no root cutting) evident in years 11, 13, and 14 for the trench treatment and years 11, 13, 14, 15, and 17 for the barrier treatment (Table 10.1). Low precipitation levels relative to evapotranspiration rates in the late growing season (Figure 10.1) may have been partly responsible for the lack of a significant root treatment effect on tree diameter growth in year 12 (barrier and trench) and year 15 (trench). Trees typically increase diameter growth in the late growing season after plant investment in photosynthetic tissues and branching is complete (e.g. Côté et al. 1998). The tree root treatments, despite reducing tree growth rates in most years, did not result in significantly different tree diameters relative to the control until year 17 (6 years after tree root pruning) and only for the most severe root manipulation treatment (barrier) ($P=0.0438$) (Table 10.1). Annual tree diameter growth rate differences between the most severe root treatment (barrier) and control, initially (year 11) as high as 0.4 cm year^{-1}, averaged only 0.2 cm year^{-1} in years 16 and 17. Black walnut annual diameter growth for the intermediate root treatment (trench) was not significantly different from the control from year 14 onwards.

Black walnut tree annual productivity was able to recover immediately after the root treatments with only a modest decrease (0.9–2.0 cm) in tree diameter compared to the control (no root pruning) after 6 years depending upon the severity of the root manipulation treatment. The tree root treatments imposed in this study were quite severe in order to separate belowground from aboveground competition

Table 10.1 Root treatment effects on mean tree diameter and diameter growth measured at breast height (dbh) of agroforestry black walnut (*Juglans nigra* L.) trees at SEPAC (Butlerville, IN, U.S.A.) and grouped according to years immediately following major tree management operations. No tree diameters were measured in year 16. Trees were planted in the spring of 1985 (year 1) and root treatments were initiated in the spring of 1995 (year 11)

	Tree diameter			*Annual tree diameter growth*		
Year	Control	Trench	Barrier	Control	Trench	Barrier
			cm			
11	11.0A[a]	11.1A	10.6A	1.6a[b]A	1.2aB	1.2aB
12	12.0A	12.0A	11.5A	0.9bA	0.8bA	0.9bA
13	13.0A	12.7A	12.1A	1.0bA	0.7bB	0.6cB
14	14.3A	13.9A	13.3A	1.3cA	1.2aAB	1.2aB
			Following thinning			
15	16.5A	15.7A	14.9A	1.5A	1.4A	1.2B
			Following branch pruning			
17	19.5A	18.6AB	17.5B	1.5A	1.4A	1.3B

[a] Within rows, treatment means followed by the same uppercase letter for diameter and growth measurements are not significantly different at the $P=0.05$ level according to LSMEANS comparisons. (From SAS Institute, 2001.)

[b] Within columns, treatment means for diameter growth followed by the same lowercase letter are not significantly different at the $P=0.05$ level according to LSMEANS comparisons. (From SAS Institute, 2001.)

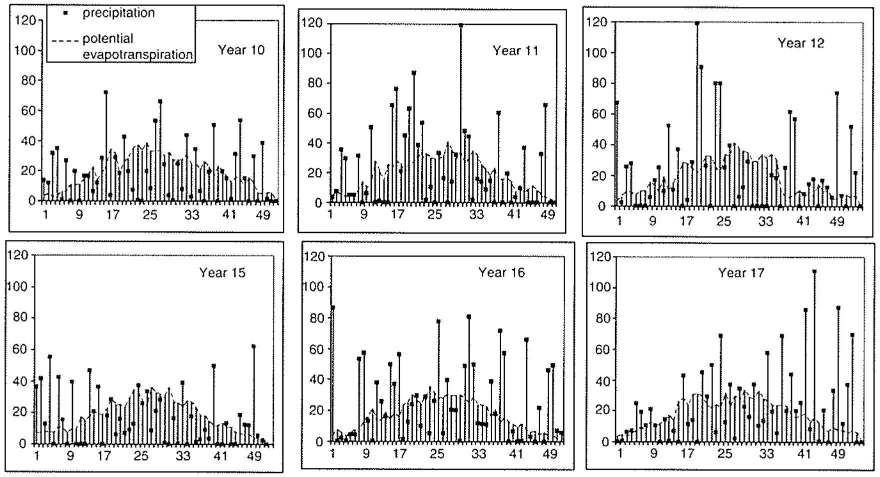

Figure 10.1 Weekly precipitation (mm) and reference evapotranspiration (mm) (ET_o; FAO Penman Monteith; Allen et al., 1998) at SEPAC (Butlerville, IN)

(Gillespie et al. 2000), but normal management of tree root competition would only cut surface roots with operations like knifing of fertilizer or cultivation for weed management. Another facet that will need investigation is the impact of black walnut root pruning treatments on veneer-grade bole quality and log value. The impact of intensive management of black walnut trees on end-of-rotation log values has only recently received attention (Bohanek and Groninger, 2003).

In year 12, the black walnut tree root manipulation (barrier) resulted in significantly lower tree fine root (<2 mm in diameter) biomass at row 1 (alley edge) (P = 0.0297; Jose et al. 2000a) relative to the control, but not at row 3 (mid alley) (P = 0.060) (Table 10.2), probably because tree roots in the control plots had still not occupied the entire 8.5-m wide alley. In contrast, in year 16, 5 years after the root manipulation, the barrier treatment had no significant effect relative to the control on tree fine root biomass (0–90 cm) at row 1 (alley edge), but instead was significantly lower at row 3 (mid alley) (P = 0.0133) relative to the control. In year 16, barrier fine-root biomass at the mid-alley position was significantly lower relative to the control plots at the 30–60 cm (P = 0.0453) and 60–90 cm (P = 0.0079) soil depth intervals, but not at the 0–30 cm soil depth interval (P = 0.853). To summarize, the barrier root treatment resulted in a significant reduction in belowground root biomass at the alley edge (row 1) in year 12 and at the mid alley (row 3) in year 16, which probably indicated a delayed-response treatment effect as the black walnut tree roots grew towards the mid alley over 4 years. Tree roots overtopping the barrier treatments and tree root exploration of areas within the tree row for the barrier treatment probably accounted for the decreasing differences in black walnut tree growth in barrier plots relative to the control plots across the period since root treatments were installed (year 11–17) (Table 10.1).

Table 10.2 Root treatment effects on black walnut (*Juglans nigra* L.) fine root (<2 mm in diameter) biomass (kg ha^{-1}) for two alley positions (row 1 = alley edge and row 3 = mid alley) and three soil depth intervals immediately after root pruning (year 12) and 5 years later (year 16) in the alley-cropping system at SEPAC (Butlerville, IN, USA)

	Alley position				
	Row 1			Row 3	
Depth	Control	Barrier		Control	Barrier
Cm	Dry fine roots (kg ha^{-1})				
	Year 12[b]				
0–30	996.0A[a]	30.7B		186.9A	22.1A
30–60	164.9A	19.7B		113.8A	15.3A
60–90	86.0A	18.2B		49.3A	2.6A
	Year 16				
0–30	1348.5A	1462.8A		940.3A	1023.0B
30–60	456.0A	363.0A		528.3A	43.9B
60–90	96.9A	166.6A		175.7A	0.0B

[a] Within rows, means from each alley position followed by the same letter are not significantly different at the P = 0.05 level.

[b] Year 12 data are from Jose (1997).

Tree root distributions measured in year 12 and year 16 indicated that black walnut fine roots were most abundant (~60–90% of total) at the 0- to 60-cm soil depth interval with total fine root biomass depending upon management. Although root biomass measurements do not necessarily represent roots actively taking up soil nutrients and water (Lehmann, 2003), the temporal tree root data reported here suggests that black walnut roots are tenacious enough to require moderate but regular pruning for reducing the risk of tree competition on alley resource availability relative to the control.

In year 2 and year 3 after black walnut agroforestry system establishment (year 1 = 1985), higher maize grain yield at row 1 (alley edge) relative to row 3 (mid alley) (Table 10.3) was likely related to the commonly expressed field-edge effect where crop yields increase at the outermost rows of fields due to increased radiation interception. At the early stages after agroforestry system establishment, black walnut trees were apparently too small to affect maize yields. The transition to competition between black walnut trees and alley plants for aboveground or belowground resources probably occurred between year 5 and year 9 for the 8.5-m wide alley (Table 10.3). Wider tree spacing and more frequent root pruning treatments could

Table 10.3 Maize (*Zea mays* L.) grain biomass yield according to distance from the tree row (row 1 = alley edge and row 3 = mid alley) at SEPAC (Butlerville, IN, USA) grouped according to years immediately following major black walnut tree (*Juglans nigra* L.) management operations. Trees were planted in the spring of year 1 (1985) and root treatments (barrier) were initiated in the spring of year 11 (1995). Monocrop represents maize yields from the adjacent field planted in maize only (no trees)

	Control		Barrier		
Year	Row 1	Row 3	Row 1	Row 3	Monocrop
			Mg ha^{-1}		
2	10.4	8.8	–	–	7.1
3	10.7	8.8	–	–	8.8
4	5.4	4.5	–	–	6.9
9	3.1	7.4	–	–	7.9
Root treatment					
11[c]	2.86a[a]A[b]	5.27aB	5.49aB	6.52aB	7.6
12	3.98aA	6.27aB	7.76bB	7.29aB	7.5
Following thinning					
16	0.69bA	1.43bB	0.40cA	2.52bB	9.4
Following branch pruning					
17	2.18aA	4.65aB	5.14aB	5.87aB	9.0

[a] Within columns, treatment means followed by the same lowercase letter are not significantly different at the P = 0.05 level according to LSMEANS comparisons. (From SAS Institute, 2001.)

[b] Within rows, treatment means followed by the same uppercase letter are not significantly different at the P = 0.05 level according to LSMEANS comparisons. (From SAS Institute, 2001.)

[c] Year 11 and 12 data are from Jose (1997)

increase the length of time in which the alley space is free from tree competition effects, but these activities could also negatively affect tree value. The recommended tree spacing for black walnut plantations in the central midwestern USA is 3.7 m at establishment and 6.1 m after final thinning prior to harvest (Beineke, 1994). Lower planting densities of black walnut trees increases the risk of producing lower value veneer-grade walnut logs with defects (Burke and Pennington, 1989) and increases the need for frequent branch pruning to reduce log defects (Schlesinger and Weber, 1987). Previous economic analyses of black walnut agroforestry systems has demonstrated that the most intensively managed agroforestry systems lead to the highest positive internal rate of return and net present value (Garrett and Kurtz, 1983; Benjamin et al. 2000).

In the black walnut alley-cropping system, the barrier treatment resulted in significantly higher maize grain yields relative to the control (i.e. alley-cropping with no root pruning) in year 11 ($P<0.001$), year 12 ($P=0.027$), and year 17 ($P=0.044$) (Table 10.3) after system establishment (year 1 = 1985). This effect appeared to be related to maize grain reductions at the alley edge (row 1) for the control plots (Table 10.3). Tree root management (barrier) resulted in similar maize grain yields across the alley comparing the alley edge and mid alley, and this was not evident in the control plots. This suggested that maize yield reductions at the alley edge relative to the mid alley in the control plots occurred due to belowground competition from trees with maize in year 11, year 12, and year 17 and not only from light limitation.

In year 16, when maize grain yields in the black walnut alleys were the lowest for the years investigated (i.e. 65%–96% of year 12 values), the tree root pruning treatment (barrier) had no significant ($P=0.46$) effect on maize biomass. Instead, there was only a significant ($P=0.0175$) distance effect with the alley edge (row 1) having lower maize grain yields than the mid alley (row 3), and a similar significant ($P=0.0104$) trend existed relating to distance from trees for the stover biomass. This could have resulted from the observed tree shading in year 16 reducing alley radiation levels across the alley together with plant competition belowground. Rainfall rates (Figure 10.1) during the growing season appeared similar in year 16 relative to other years in which higher maize grain yields occurred (e.g. years 11 and 17). Another factor, decreasing alley light levels, seems to have limited maize yields in year 16 (Figure 10.2). Abundant lateral branches from walnut trees were present in the alleys in year 16 but were removed (~20% of the tree canopy volume removed) by pruning early in year 17. The resulting changes in alley light levels are shown in Figure 10.2. Aboveground branch pruning in year 17 apparently played a role in returning crop yields, after declines in year 16, to up to 81% of year 11 values. Light limitation was not seen in the earlier study of year 11 (Gillespie et al. 2000), but became apparent as the black walnut alley-cropping system developed, crowns closed, and the alley became shaded in year 16. Miller and Pallardy (2001) observed early light limitation on maize productivity with silver maple by year 7 after establishment using a wider (19.5 m) alley than the SEPAC site (8.5 m) and a faster growing tree species than black walnut. Species and alley width selection will influence the spatial and temporal dynamics of plant competition for alley resources.

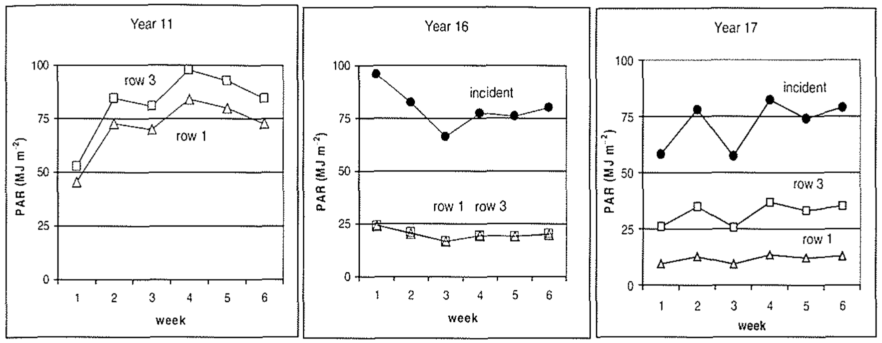

Figure 10.2 Weekly (week 1 starts June 1) incident and transmitted photosynthetically active radiation (PAR) within a black walnut-maize alley-cropping system at the alley edge (row 1) and mid alley (row 3) for years 11, 16, and 17 (no incident PAR data measured in year 11). (Year 11 data are from Jose, 1997.)

The suitability of maize as an alley crop likely ceased for the SEPAC system with an 8.5-m alley width sometime between year 12 and year 16 as indicated by alley yield comparisons to those from the adjacent monocultural field (Table 10.3). In year 17, maize grain yield at the mid alley (row 3) position was nearly 40% lower relative to the monocultural maize field in contrast to year 12 when alley maize yields in the barrier treatments were about 85% of monocultural maize yields. In year 12 and year 16, stover- and aboveground-biomass were not significantly ($P<0.05$) impacted by the tree root pruning treatment (Table 10.4) suggesting that resource capture by alley crops was still substantial despite belowground competition from trees. This alley production indicates opportunities for productive alley cropping with alley plants capable of acquiring belowground resources for biomass production despite tree competition. Maize is a resource demanding crop (C4 carbon assimilation pathway), and other crops (e.g. winter wheat (*Triticum aestivum*) or barley (*Hordeum vulgare*) with C3 carbon assimilation pathways) likely were better options for alley management after year 12 in the intensively managed hardwood alley-cropping system.

Agroforestry Management Effects on Soil Water Content

The black walnut barrier treatments did not result in significantly different soil volumetric water contents, when averaged across all distance from tree and soil depth combinations, from the control (i.e. agroforestry with no root pruning) plots for either year 12 ($P=0.112$) or year 16 ($P=0.188$) (year 1 = 1985). However, a treatment interacting with distance (tree row, row 1, and row 3) and depth (0–30, 30–60, 60 – 90 cm) effect on soil water levels was marginally significant in year 12 ($P=0.0695$) and a treatment interacting with distance effect on soil water was also discernible in year 16 ($P=0.0539$).

Table 10.4 Maize (*Zea mays* L.) stover and maize aboveground biomass by alley-row position (row 1 = alley edge and row 3 = mid alley) at SEPAC (Butlerville, IN, USA). Trees were planted in the spring of year 1 (1985) and root treatments (barrier) were initiated in the spring of year 11 (1995)

	Maize Stover				Maize aboveground biomass			
	Row 1		Row 3		Row 1		Row 3	
Year	Control	Barrier	Control	Barrier	Control	Barrier	Control	Barrier
				Grain Mg ha^{-1}				
12[a]	3.9A[b]	5.8A	4.7A	6.0A	8.36A	13.7A	11.0A	13.0A
16	2.6A	2.6A	3.4A	4.7A	3.27A	3.0A	4.9A	7.2A

[a] Year 12 data are from Jose (1997).

[b] Within rows and alley position (row 1 and row 3), treatment means for maize biomass component followed by the same letter are not significantly different at the P=0.05 level according to LSMEANS comparisons. (From SAS Institute, 2001.)

In year 12 after establishment of the black walnut alley-cropping system, the barrier treatment resulted in a significantly higher soil moisture level in the surficial soil ($\theta_v = 0.25 \pm 0.01\,cm^3cm^{-3}$) across the growing season relative to the control (no root pruning) ($\theta_v = 0.20 \pm 0.01\,cm^3cm^{-3}$) at the mid-alley (row 3) position (P=0.0457), but not at the alley edge (row 1) position (P=0.277) or tree row (P=0.336). However, trends of increasing soil water content for the barrier treatment relative to the control were apparent at the alley edge (Figure 10.3a). In year 12, there was no significant barrier treatment effect on soil water content for the subsoil depth intervals (30–60 and 60–90 cm) at any distance (alley edge and mid alley) from the tree row (Figure 10.3b-c). This could have resulted because tree roots had not yet substantially grown into the mid alley at the subsoil (30–60 and 60–90 cm) depths in the control plots in year 12 (Table 10.2).

In year 16 after establishment of the black walnut alley-cropping system, there was no significant treatment (barrier) effect on soil volumetric water content relative to control plots (no root pruning) at the mid-alley position (row 3) (P=0.332) and within the tree row (P=0.124). Rainfall and proximity to the tree canopy drip line at the mid alley may have provided adequate soil moisture so trees did not compete for soil water with alley crops in year 16 resulting in the lack of a treatment difference. However, there was a significant reduction in soil moisture levels at the alley edge (row 1) for the barrier treatment relative to the control (P=0.0219) (Figures 10.3a–c). This pattern of soil moisture contents within the alley-cropping system in year 16 differed substantially from that in year 12. In year 12, there was a significant treatment (barrier) effect on increasing soil moisture levels at the mid alley (row 3) position relative to the control (no root pruning); however, in year 16 the treatment resulted in reduced soil moisture contents at the alley edge (row 1) relative to the control. Soil moisture reductions due to the barrier relative to the control (no root pruning) at the alley edge in year 16 were apparent at all three soil depth intervals (0–30, 30–60, and 60–90 cm) and were likely related to the increase in walnut root biomass over time (Table 10.2) from tree roots overcoming the plastic barrier and entering the alley. Thus, tree root management at the alley edge with barriers resulted in increased competition for soil moisture relative to the control (no root pruning) after six years. Tree competition for water likely occurred deeper in the soil profile at the alley edge by year 16 relative to year 12. Excavation of trenches creating pits for root distribution visualization across the alleys between tree rows revealed a distinct increase in tree fine roots within the tree row area adjacent to the barrier plastic in both year 12 (Jose et al. 2000a) and year 16. Trees apparently responded to the barrier treatment by increasing rooting within the tree row area.

(a)

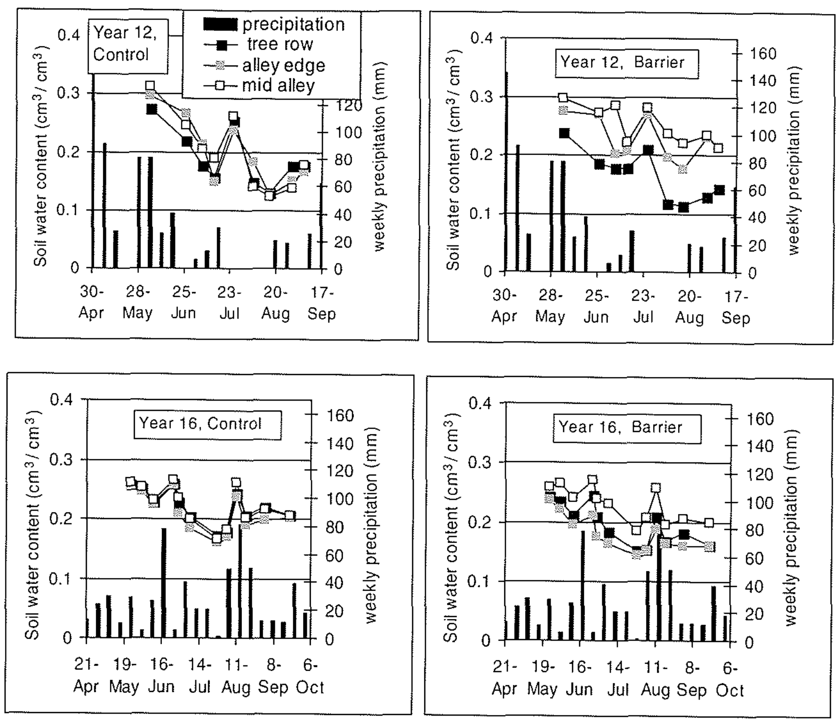

Figure 10.3a Soil water contents at a 0- to 30-cm soil depth in years 12 and 16 since establishment of a black walnut–maize alley-cropping agroforestry system in southern Indiana, USA. (alley edge = row 1; mid alley = row 3) (year 1 = 1985).

The lower soil water contents in year 16 versus year 12 (Figures 10.3a–c), especially in the subsoil may have resulted because of poor recovery in year 16 from the strong droughty conditions in year 15 (Figure 10.1) combined with increasing tree moisture depletion due to the growing trees increasing the water demands. Rainfall quantities in year 12 and year 16 did not appear substantially different (Figure 10.1), but growing trees could reduce soil moisture contents by accessing a greater volume of soil as well as by increasing canopy rainfall interception from a larger crown volume. Soil moisture levels were lower in year 16 than in year 12 particularly in the subsoil, but soil moisture was well above (wetter) the permanent wilting point (PWP=–1.5 MPa) for the Ryker silt loam soil in the surficial soil, with soil matric potentials averaging >–0.1 MPa at the most droughty location (barrier, row 1) on the agroforestry site in year 16 (von Kiparski, 2000 (unpublished data)). This indicated that the soil moisture levels in year

(b)

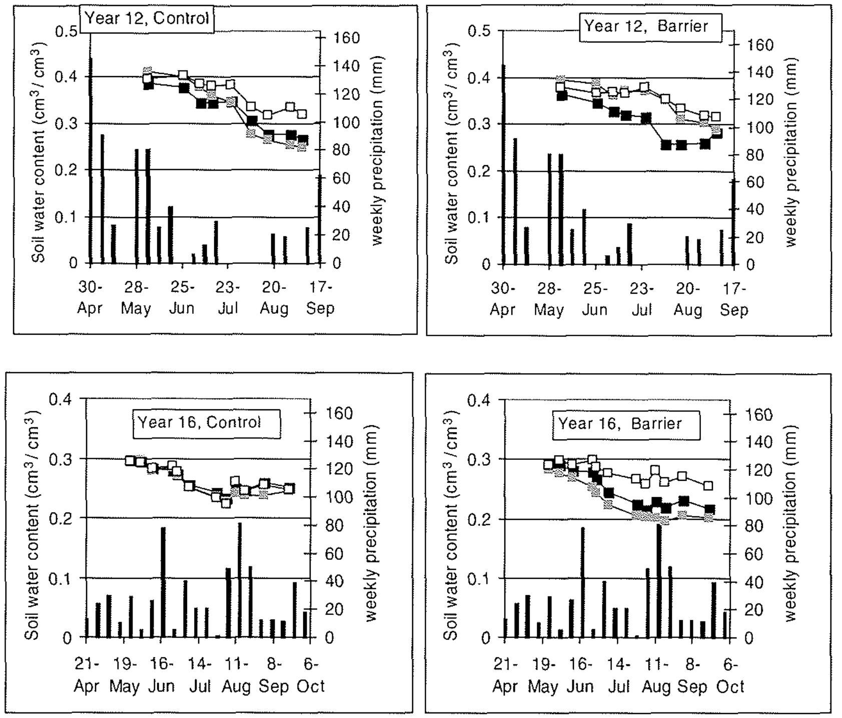

Figure 10.3b Soil water contents at a 30- to 60-cm soil depth in years 12 and 16 since establishment of a black walnut–maize alley-cropping agroforestry system in southern Indiana, USA. (alley edge = row 1; mid alley = row 3) (year 1 = 1985). Legend is in Figure 10.3a.

12 and year 16 were probably adequate in surficial soil layers for plant growth because of frequent rainfall throughout the growing season; however, for crops susceptible to diurnal or short-range droughty conditions, the biweekly soil moisture measurements reported here may have not captured stressed conditions in the soil for vulnerable plants. For example, maize is dependent upon having adequate soil moisture during a small 2-week period around grain set (e.g. Schussler and Westgate, 1991). These requirements made maize an unsuitable grain crop for alley cropping after year 12 since system establishment.

Agroforestry Management Effects on Soil N Productivity Vectors

Black walnut tree competition for fertilizer N with the alley crops was assessed using ^{15}N-labeled fertilizer additions and tracing the ^{15}N uptake by alley maize grain and stover biomass accumulated after one growing season. In year 12, maize plants growing in the barrier treatment yielded a lower percentage of N derived from fertilizer (%NDF) in grain (P=0.021) and stover (P=0.043) relative to the control (no root pruning) (Jose et al. 2000b) (Table 10.5). The higher total N uptake in year 12 maize grain (P=0.013) and stover (P=0.004) from the barrier treatment relative to the corresponding maize components of the control was attributed to increased soil native N availability in the barrier plots relative to the control plots (Jose et al. 2000b). This could have resulted from higher N mineralization rates in the barrier due to higher soil moisture levels than the controls (no root pruning), or alternatively exclusion of tree tissues from the alley soil may have improved overall litter quality and nutrient availability.

(c)

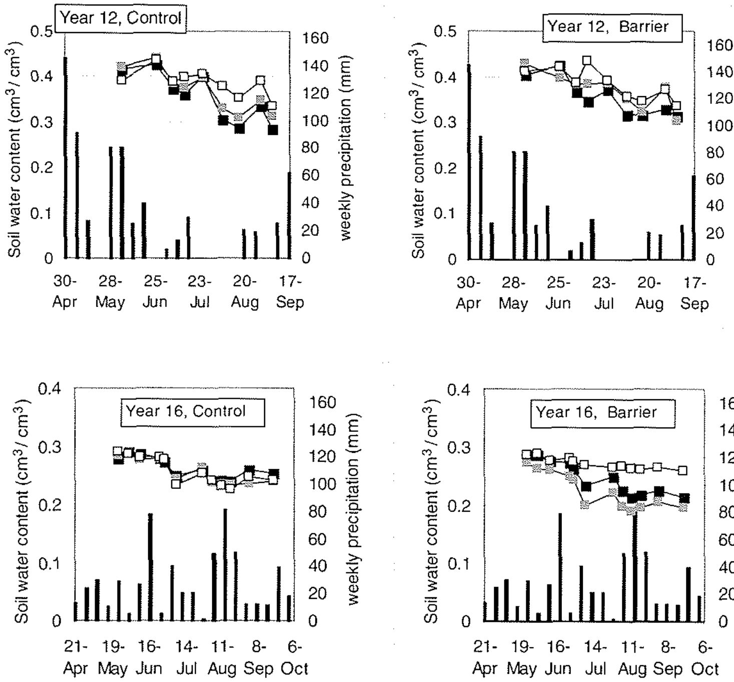

Figure 10.3c Soil water contents at a 60- to 90-cm soil depth in years 12 and 16 since establishment of a black walnut–maize alley-cropping agroforestry system in southern Indiana, USA. (alley edge = row 1; mid alley = row 3) (year 1 = 1985). Legend is in Figure 10.3a.

In year 16, maize grain N uptake was <18% of year 12 levels and stover N uptake was <64% of year 12 levels (Table 10.5). Nitrogen uptake in grain (P=0.356) of the alley crop in year 16 did not significantly differ between barrier and control plots. A similar lack of treatment difference in %NDF in maize grain (P=0.786) and stover (P=0.711) between the barrier and control was also observed (Table 10.5). The low alley light levels in year 16 could have contributed to the low maize N uptake from fertilizer and native soil N because of reduced plant growth from reductions in light capture (photosynthesis). In year 16, the alley crops acquired a lower proportion of

Table 10.5 Nitrogen and ^{15}N uptake by maize (*Zea mays* L.) components in year 12 and year 16 with percent nitrogen derived from fertilizer (%NDF) and fertilizer use efficiency (%UFN) in the maize biomass (year 1 = 1985). (row 1 = alley edge; row 3 = mid alley)

		Nitrogen content		%NDF[a]		%UFN
Treatment	Row	Grain	Stover	Grain	Stover	Grain + Stover
		kg ha^{-1}		%	%	%
				Year 12[b]		
Barrier	1	107.4	75.6	42.9	46.9	48.3
	3	97.2	77.3	42.6	45.9	46.0
	Mean[c]	102.0	76	42.7	46.4	47.2
Control	1	68.4	51.8	54.7	57.4	40.0
	3	77.4	55.7	47.3	49.0	37.8
	Mean	73	54	51.0	53.2	38.9
	P-value[¶]	0.013	0.004	0.021	0.043	0.073
			Year 16			
Barrier	1	3.7	35.8	44.2	46.5	8.7
	3	30.3	55.2	28.9	33.8	13.7
	Mean	18.3	48.6a	36.5	40.2	11.2
Control	1	4.0	21.6	37.7	37.7	4.1
	3	28.7	43.8	24.0	44.4	13.8
	Mean	13.6	38.6	32.1	41.1	9.0
	P-value	0.356	0.289	0.786	0.711	0.618

P-values are for treatment mean comparisons within years.

[a] Percent nitrogen derived from applied mineral N fertilizer (%NDF) was calculated as: %NDF = 100 × a/b. where a is the excess atom%^{15}N in the tissue above that in the control (background levels = excess atom%^{15}N = 0.3663), and b is the excess atom%^{15}N in the $(NH_4)_2SO_4$ fertilizer applied. (From Hauck and Bremner, 1976.)

[b] Year 12 data obtained from Jose et al. (2000a).

[c] Mean represents the treatment mean (row 1 and row 3 combined).

N as fertilizer N relative to year 12, particularly within the control areas. In addition to the aforementioned reductions in alley light levels, evidence of unavailable fertilizer N could have resulted from the presence of significant quantities of residual soil inorganic N from year 15 causing isotope pool substitution. Year 15 was a droughty year (Figure 10.1) and the maize yields were negligible (von Kiparski, 1999 (unpublished data)) potentially leaving year 15 fertilizer in the soil as carryover N for year 16. Increased competition for N by black walnut trees could also have contributed to the decrease in fertilizer N uptake in year 16; although, Jose et al. (2000b) reported that black walnut trees in year 12 trees took up only 1.9% of the fertilizer N inputs applied within 1 year. In year 16, the black walnut trees were significantly larger than 4 years earlier. Standing aboveground biomass of black walnut trees was estimated to be 32.2 Mg ha^{-1} carbon with 158.9 kg N ha^{-1} in year 17, compared to only 11.4 Mg ha^{-1} carbon and 56.8 kg N ha^{-1} in year 12. Thus, carbon and nitrogen accumulation by trees had nearly tripled in only 5 years and could have increased N competition by trees on the alley plants for nitrogen.

Soil solution inorganic nitrogen (DIN) concentrations at the 90-cm depth (Figure 10.4) represent soil N potentially lost from the agroforestry cropping system because of a lack of crop and tree rooting at that depth (Table 10.2). Nitrate-N was the form of nitrogen that dominated (>86%) the DIN pool in the subsoil. In the year 16 growing season, there was a significant interaction effect of root treatment, date and distance (alley-row position) on soil DIN levels. The barrier treatment resulted in significantly ($P<0.05$) higher soil DIN concentrations (90-cm depth) within the cropping alley on four of ten dates during the growing season at the alley edge (row 1) and on five of ten dates at the mid alley (row 3) (Figure 10.4). For example, on June 27 in year 16, the inorganic N concentration in soil solution (90-cm depth) at the alley edge averaged 16.6 mg L^{-1} (SE = 1.6) in the barrier plot, but was lower 5.8 mg L^{-1} (SE = 2.3) in the control plot (no root pruning). An adjacent agricultural field fertilized at the same rate and under similar maize management except without trees had elevated inorganic N concentrations (e.g. 12.1 mg L^{-1} (SE = 2.6) on June 27), but was not included in the comparison with the agroforestry area across sampling dates since it only consisted of a single replicated field. The tree row areas were not N fertilized and as expected had consistently low inorganic N concentrations at the 90-cm depth across the growing season (DIN = 1.7 mg L^{-1}, SE = 0.28). At the mid-alley (row 3) position in year 16, there was no significant difference in subsoil soil water content between treatments (Figures 10.3b–c), which further substantiates a real reduction in soil DIN levels and not simply a concentration–dilution effect.

For the agroforestry system, the major sources of nitrogen in the leachates from year 16 were likely from accumulation of inorganic N in the alley soil profile during the droughty period in year 15, fertilizer N application from year 16, and any N mineralization that occurred from the year 16 soil organic N pool. When rains commenced in the spring of year 16, after the historically dry year 15, a substantial quantity of fertilizer N (year 15 and year 16) may have been leached to the 90-cm soil depth causing the pattern of increased N in leachates observed (Figure 10.4).

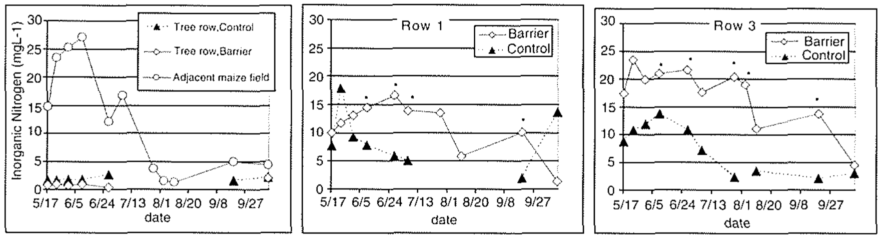

Figure 10.4 Soil solution concentrations of inorganic nitrogen (NH_4^+-N + NO_3^--N) at the 90-cm soil depth collected using porous-ceramic cup samplers in year 16 since establishment (year 1 = 1985) of a black walnut (*Juglans nigra* L.) alley-cropping agroforestry system at SEPAC (Butlerville, IN). Inorganic fertilizer was applied to the cropping alley in previous years as well as on April 27 in year 16. Soil solution concentrations of inorganic nitrogen at the 90-cm depth beneath an adjacent maize field were plotted for comparison.

Reductions in DIN levels in the subsoil as the growing season proceeded (Figure 10.4) could have reflected uptake of N from the subsoil (90-cm depth). However, because of the sparse rooting in the alley subsoil (Table 10.2), the soil DIN levels at the 90-cm depth probably represented soil N that could be lost from the site as leachate, especially during periods when precipitation exceeded evapotranspiration rates.

Nitrogen ^{15}N-labeled fertilizer from the year 16 (April 27) application was present in the barrier leachates at the 90-cm depth at the mid alley (row 3) position, but not at the alley edge (row 1) position during the year 16 growing season (Table 10.6). This could reflect tree uptake of fertilizer N from locations in the soil above the 90-cm depth where tree roots were competing for fertilizer N with the alley maize crop. Since previous year fertilizer was not ^{15}N-labeled nitrogen, N from these fractions dissolved in soil solution could also have contributed to the reduction in the ^{15}N label of soil solution. On a number of occasions during year 16, the row 1 samplers failed to collect in the control plots due to droughty conditions precluding soil solution collections. The soil solution samplers are effective in sampling water at a soil moisture potential of -0.07 MPa or higher. On those occasions when soil lysimeters were wet enough to collect soil solution, the row 1 soil samplers never contained any detectable ^{15}N-labeled nitrogen indicating that trees possibly removed the ^{15}N-labeled fertilizer by uptake from the alley edge in contrast to the mid alley position. In the control areas of the black walnut alley-cropping system where tree roots were allowed to grow freely, the low soil DIN concentrations at the 90-cm depth were most likely resulted from a tree capture effect. Tree N capture could provide a useful means to increase fertilizer-use efficiency on farmlands. The hardwood alley-cropping systems could potentially serve as buffer areas surrounding conventional cropping areas in order to capture N moving offsite and inaccessible to grain crops.

Black walnut tree management apparently affected soil labile organic nitrogen levels in the alley-cropping system in year 18 after system establishment (year 1 = 1985). Tree root manipulation (barrier) resulted in significantly lower soil amino-sugar N levels at the alley edge (row 1) ($P = 0.0460$), but not at the mid alley (row 3) ($P = 0.710$) (Figure 10.5). There was no significant difference in soil amino sugar N levels for row 1 and row 3 ($P = 0.794$). The effects of trees on soil fertility enrichment might also have been less obvious in this system receiving regular fertilizer inputs. It is possible that long-term (i.e. 18 year) contributions from tree root turnover in the control plots provided a source of labile N to the soil that was not evident in the barrier plots. Amino acids and sugars are two principle components of root exudates (Jones et al. 2004) and amino-sugar N fractions are representative of microbially altered organic matter and are components of both bacterial and fungal organisms (Stevenson, 1982). Zhang et al. (1999) reported that afforestation over 80 years reduced soil amino-sugar N concentrations (0–10 cm soil depth) by 13% relative to grassland areas. In the SEPAC black walnut alley-cropping system, undisturbed (i.e. no root management) tree growth was associated with higher soil labile organic N concentrations perhaps by capturing and recycling fertilizer N additions (e.g. van Noordwijk and de Willigen, 1991).

Table 10.6 Dissolved inorganic nitrogen (DIN) concentrations and nitrogen derived from fertilizer (%NDF) in soil solution samples collected in year 16 (year 1 = 1985) from the 90-cm soil depth of the Ryker silt loam using porous ceramic-cup soil solution samplers within the alleys at two distances (row 1 = alley edge and row 3 = mid alley) from the tree row of a black walnut alley-cropping system

	Row 1		Row 3	
Date	Control	Barrier	Control	Barrier
	DIN			
		mg L^{-1}		
May 18	11.8	9.5 (7.7)	Dry	13.5 (5.0)
May 24	Dry	12.5 (9.8)	9.0 (7.6)	23.4 (4.7)
June 1	Dry	18.6	Dry	24.5 (4.7)
June 10	9.4 (0.5)	12.9 (8.0)	19.7	20.6 (0.6)
June 25	Dry	21.5 (0.9)	10.1	22.4 (5.2)
June 28	Dry	17.4 (0.4)	1.7	30.9 (3.7)
	%NDF[a]			
		%		
May 18	0	0	Dry	1.6 (1.6)
May 24	Dry	0	35.2 (21.0)	9.9 (8.9)
June 1	Dry	0	Dry	0
June 10	0	0	64.6	18.2 (9.5)
June 25	Dry	0	59.5	23.5 (12.6)
June 28	Dry	0	5.8	32.6 (5.2)

[a] Percent nitrogen derived from applied mineral N fertilizer (%NDF) was calculated as: %NDF = 100 × a/b where a is the excess atom%^{15}N in the leachate above that in the control (background levels = excess atom%^{15}N = 0.3663), and b is the excess atom%^{15}N in the $(NH_4)_2SO_4$ applied. (From Hauck and Bremner, 1976.)

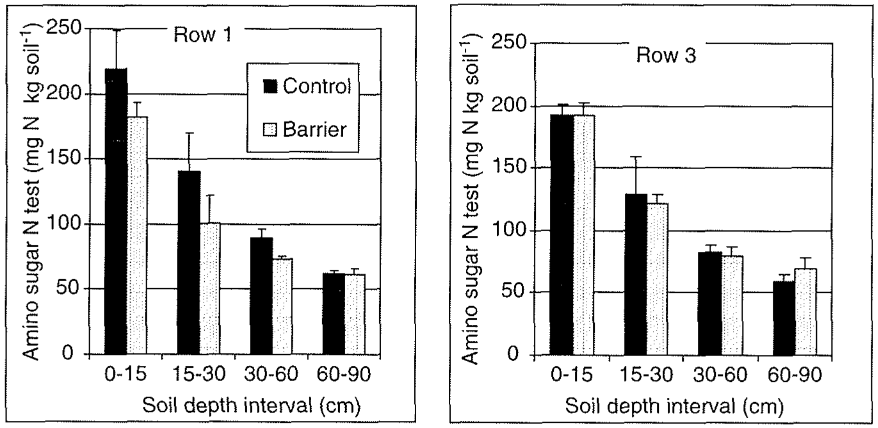

Figure 10.5 Amino sugar nitrogen (N) contents of alley soils in year 18 after establishment (year 1 = 1985) of a black walnut (*Juglans nigra* L.) alley-cropping agroforestry system at SEPAC. Tree root pruning treatments (barrier) were applied in year 11. Error bars indicates standard errors of the means

The black walnut agroforestry system, although regularly fertilized in previous years and with apparent labile organic N inputs from tree litter, still was determined to require fertilizer N additions in order to satisfy maize grain production. In the surficial soil (0–15 cm depth), the control (i.e. agroforestry with no root pruning) averaged 219 ± 30 mg N kg^{-1} as amino-sugar N, the barrier treatment averaged 182 ± 11 mg N kg^{-1}, and an adjacent maize field (i.e. similar land use history, but without walnut trees) averaged 186 ± 11 mg N kg^{-1}. These soil amino-sugar N levels indicated that maize planted in year 18 would have been responsive to N fertilization inputs in either the monocultural field or the agroforestry system alleys since soil amino-sugar N levels were below the amino-sugar N threshold (235 mg N kg^{-1}) for fertilizer responsiveness established by Khan et al. (2001) for monocultural maize on a set of Illinois soils (with properties inclusive of the Ryker silt loam soil).

Slow labile organic N accumulation from trees, low inherent fertility of the weathered Ryker soil, or perhaps competitive demands by trees could have limited the soil accumulation of the labile organic N contributed from 18 years of black walnut tree growth. In humid tropical regions, regular tree-coppicing (mulch) fertilizer inputs from fast-growing nitrogen fixing trees (e.g. *Leucaena* spp., *Gliricidia* spp.) can increase soil fertility in only 2 or 3 years (Kang et al. 1990); in temperate regions, with N-fixing species (*Alnus sinuta*) and regular mulch additions, there was also a fast benefit to soil fertility improvement following only 4 years (Seiter and Horwath, 1999). Laboratory incubations of temperate agroforestry tree litter suggest small positive or negative impacts on available nitrogen pools depending upon incubation conditions and litter quality (Thevathasan, 1998; Jose et al. 2000b; Mungai and Motavalli, 2005). Additional research to adapt soil testing such as the amino-sugar N test for agroforestry will benefit efforts to optimize fertilizer application on the temperate alley-cropping system.

Agroforestry Management Effects on Soil Carbon Concentrations

The SEPAC soil organic carbon concentration was measurably higher though not significantly higher (P = 0.0566) in the agroforestry barrier treatment relative to the control (i.e. no root pruning) within the black walnut agroforestry system alleys (Figure 10.6) in year 16 (year 1 = 1985), 5 years after the root pruning treatments were installed. In addition, the tree row had measurably higher concentrations of soil organic carbon than the cropping alley, but these differences were also not significant (P = 0.0614). A discernible treatment *x* depth interaction (P = 0.0989) effect on soil organic carbon levels indicated a trend of higher soil organic carbon for the barrier plots at the 15–30 (P = 0.0494) and 30–60 cm (P = 0.0168) depths relative to the soil organic carbon levels at the corresponding depths in the control plots. There was no evidence for a similar treatment effect on soil total N (P = 0.717).

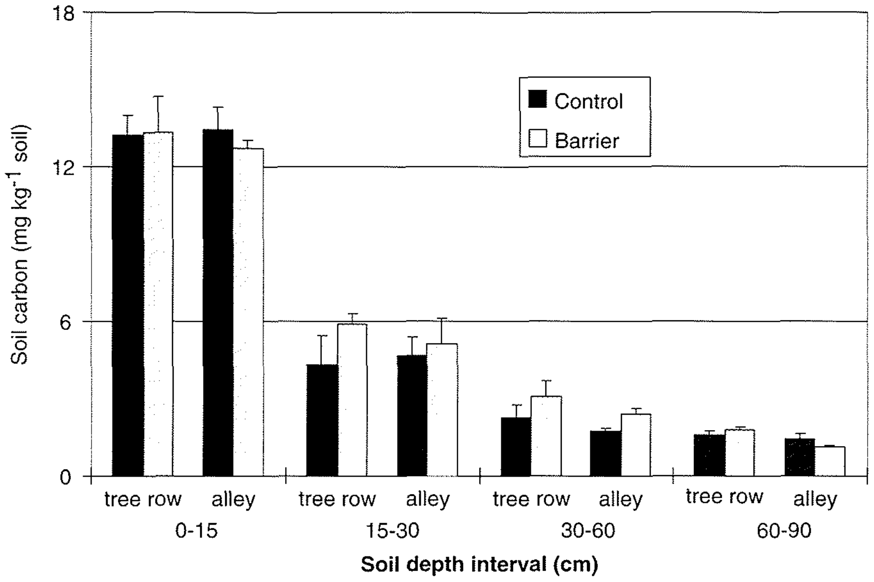

Figure 10.6 Soil carbon concentrations plotted versus soil depth interval (0–15, 15–30, 30–60, and 60–90 cm) in year 16 after establishment (year 1 = 1985) of a black walnut (*Juglans nigra* L.) alley-cropping system at SEPAC. Tree root pruning treatments (barrier) were applied 5 years previously. Agroforestry row position (tree row and alley) is also indicated. Error bars indicate the standard errors of the means

The measurable increase in soil organic carbon content at the 15–60 cm depths within the barrier treatment may have resulted from contributions both from the tree row as well as the mid alley (row 3) position given the lack of any significant row *x* treatment interaction. Tree rhizodeposition and root pruning in the SEPAC alley-cropping system apparently contributed to soil carbon sequestration, and the former is one suspected result of afforestation in general (Kimble et al. 2003). Mungai et al. (2005) reported soil organic C and N distributions in a 21-year-old pecan (*Carya illinoinensis* L.) and 12-year-old silver maple (*Acer saccharinum* L.) alley-cropping systems in relation to distance from the tree row to a soil depth of 0–30 cm. They observed a tree effect on increasing soil organic carbon and nitrogen (Total Kjeldahl N) levels at the 0–30 cm depth in the tree row for the Maple site but not at the Pecan site. Thevathasan and Gordon (1997) documented that higher soil carbon contents formed in the tree row relative to the mid alley during hybrid poplar growth over a period of 8 years. At the SEPAC site, trends of increasing soil organic carbon in agroforestry tree rows were evident, but not yet significant after 17 years of system development and after 5 years since root pruning. These early trends after SEPAC system establishment suggest that soil carbon stabilization associated with tree litter inputs could become significant over a tree harvest cycle (e.g. 40–80 years).

Conclusions

Hardwood alley-cropping systems are still under development as land-use systems, and little information exists regarding production factors and management challenges for the system as the hardwood trees grow. This study explored system productivity and resource productivity vectors within a maturing (1- to 18-year-old; year 1 = 1985) black walnut alley-cropping system at SEPAC subjected to tree root management designed to separate below- from aboveground competition in year 11. Intensive system management included regular branch pruning as well as the single set of root pruning treatments.

These management activities were effective in increasing the maize yield at SEPAC with respect to the control (no root separation) at the alley edge so that even 6 years after installation, maize productivity was comparable across the alley rows, despite shading from the tree row at the alley edge. However, reductions in maize productivity in the agroforestry system relative to the adjacent monocultural field were eventually substantial indicating that the suitability of maize as an alley crop ceased for this system with an 8.5-m alley width sometime after year 12 but before year 16 after establishment. The root treatment with plastic barrier insertion (barrier) immediately affected tree diameter growth and significantly reduced tree diameters after six years since root treatment installation. In contrast, the root pruning treatment with trenching, but no polyethylene barrier insertion (trench), resulted in rapid tree growth recoveries relative to the control so that no differences in tree diameters were evident. These management response differences indicate the tradeoffs between maintaining black walnut alley productivity and tree growth that occur depending upon the severity of the root pruning treatment.

Competition from trees reducing alley maize productivity commenced after year 4 at SEPAC, indicating an 8- to 12-year timeframe where tree root management could be effective in maintaining alley yields before excessive tree shading occurs. Resource-demanding cash crops such as maize experienced reduced yields over time indicating a significant alteration of the alley resource environment and the need for intensive management, and/or rotation to less resource-demanding crops in order to maintain system structure and function. Traditional forest and agronomic management practices can be incorporated into systems for controlling agroforestry competition by understanding the agroforestry system as a true system whose components interact through time and space. Switching to less-resource demanding crops, or increasing alley spacing can prolong the period in which crop coexistence and productivity is optimal. Based on comparison to other sites, the initial tree spacing decision and tree species selection will control the rate at which changes in alley resource productivity vectors develop and future research should discover the most promising tree-crop combinations and management.

Black walnut tree roots had a "safety net" effect within the cropping alley by decreasing the quantity of inorganic and fertilizer nitrogen found in deep soil leachates. Frequent rainfall in this humid region in combination with surficial tree root management could allow for plentiful soil moisture and N in surface horizons while maintaining the N capture effect by trees deeper in the soil profile. Root management resulted in trends of increasing soil carbon stabilization in the alleys after only 5 years. However, the hardwood tree rooting was associated with significantly increased pools of labile soil organic N (amino sugar N) within the effective rooting zone of the cropping alley. These organic N sources might benefit the system by replacing fertilizer N requirements in the cropping alley, although these effects still have not been tested. It is unclear whether hardwood alley-cropping trees will provide a slow enrichment of soil fertility relative to the systems specifically designed for soil fertility improvement, or whether the trees instead deplete soil nitrogen over time as has been observed in plantation forestry systems (e.g. Richter and Markewitz, 2001).

The results presented here show that hardwood alley-cropping systems have significant potential for increasing the economic viability of plantation forestry as well as enhancing the long-term productivity and conservation of soil and groundwater resources on vulnerable agricultural landscapes. Management of resource productivity vectors in these spatially and temporally complex systems will need to find the right balance between alley and tree productivity over time, a balance which maximizes the positive effects of the several positive functionalities found within this system.

Acknowledgments We would like to thank Dr. Shibu Jose and Dr. Tamara Benjamin for their earlier research on the field site, and John Seifert and Don Biehle for their assistance with fieldwork and data collection. We gratefully acknowledge funding from the USDA NRI Soils and Soil Biology Program. We also thank Drs. Judy Santini and Eileen Kladivko of the Purdue University Agronomy Department as well as Drs. Richard Mulvaney and Saeed Khan for their kind assistance and advice during this research. Finally, we would like to thank the two anonymous reviewers of an early version of this manuscript.

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Chapter 11
Root Competition for Phosphorus Between Coconut Palms and Interplanted Dicot Trees Along a Soil Fertility Gradient in Kerala, India

H.B.S. Gowda[1] and B.M. Kumar*,[1]

Introduction

Homegardens are archetypal land-use systems in the tropics. They involve diverse kinds of trees and field crops that coexist in apparent harmony and in close juxtaposition with one another (Kumar and Nair, 2004). In the peninsular India, coconut palms (*Cocos nucifera*) form the "nucleus" of these gardens, around which the other components are orchestrated (Jose and Shanmugaratnam, 1993). Several multipurpose trees and shrubs also occur in homegardens. These include trees scattered around the homesteads and trees planted at specific points to provide or avoid shade, necessary or harmful to different plants, besides trees providing support to vines such as *Piper nigrum* (Mathew et al. 1996). In addition, many farmers integrate fast growing timber species in well-fertilized plantations (e.g. coconut) in expectation of extra cash returns. Indeed, the steadily rising timber prices in the local and regional markets of peninsular India have given an impetus to such intercropping practices.

Inter-specific interactions affecting resource capture by the component species are, however, crucial in these multi-strata systems (Kumar et al. 1999). Root systems of different components in the homegardens also may overlap considerably and have implications (negative by deduction) in determining productivity. In particular, asymmetric competition (resource acquisition at differential rates; Weiner, 1990; Wedin and Tilman, 1993) and thereby resource pre-emption by the dominant component of a competing mixture are thought to be crucial in such mixed species systems.

Furthermore, differences in belowground resource acquisition capabilities (e.g. rooting characteristics) are probable among the associated species. Such differences also get magnified during the course of competitive interactions (Grime, 1979; Keddy, 1989), implying their dynamic nature. This in turn, may be dependent

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

on site fertility also. Although agronomists generally recommend "adequate and separate" fertilizer doses for all component crops in a mixed species system to avert potential nutrient limitation, ecologists consider such interrelationships highly complex. As a result, divergent views on the relative magnitude of belowground competition and resource availability (nutrient poor soils vs. nutrient rich soils) have been articulated (see synthesis by Grubb, 1994). Experimental studies, especially those in the natural ecosystems (Campbell et al. 1991; Pysek and Leps, 1991), have led to the suggestion that root competition for mineral nutrients is more severe on nutrient-rich soils. Consistent with this, Keddy (1989) observed that resource competition should increase as the resources themselves increase in availability, and referred this as "the paradox of resource limitation." Another line of investigation, however, has led to the equally clear conclusion that growth inhibition resulting from root competition for mineral nutrients is more severe on nutrient-poor soils (Taylor et al. 1990; Wilson and Tilman, 1991). Despite this, little information exists on competition for belowground resources in managed land-use systems, especially for those involving two or more woody perennials, and differing resource levels. But such information is of practical significance in homegarden management as the gardeners routinely apply disparate quantities of organic manure/chemical fertilizers to the crops in these systems.

Woody perennials also have the inherent ability to recycle considerable amounts of nutrients especially after canopy closure and that their root architectural pattern may be different compared to juvenile stages. This in turn, may bring about qualitative changes in belowground resource availability and/or dynamics of root competition especially late in the rotation. While the nature and magnitude of interactions between woody perennials in managed systems are thought to be more intense as the tree components in the production system mature, there may be a concomitant increase in the nutrient cycling process with stand age, especially for the dicot trees, which produce substantial litter inputs. Detritus production in coconut palms, however, is modest and much of the dry/mature coconut leaves is also removed for fuel and thatching purposes, so that they play no further role in the nutrient recycling process. It is probable that the increasing rates of nutrient cycling may alter the magnitude of competitive/complementary interactions in mixed species systems. Although many researchers (e.g. George et al. 1996; Thomas et al. 1998; Nissen et al. 1999; Kumar et al. 2001; Rowe et al. 2001, etc.) have addressed questions relating to inter-specific interactions between dicot trees and herbaceous components earlier, no previous studies have explicitly addressed the question of belowground competition of woody perennials in mixed species systems at different stages of stand development and/or under differing resource levels. Hence a field experiment was conducted to test the hypothesis that root competition in a multispecies tree-based system may be dependent on growth characteristics (e.g. root architecture) of the trees involved rather than resource availability.

A previous experiment (Kumar et al. 1999) at the same site demonstrated the potential of ^{32}P for characterizing root interactions between coconut palms, associated dicot trees, and a herbaceous field crop (*Kaempferia galanga*) at an earlier stage of stand development (3 years after planting). However, that study was conducted when the dicot tree components were relatively smaller in size. In addition, the impact of differing resource availability on nutrient uptake by the coconut palms and dicot trees was not determined in that study. The objectives of the current study, therefore, were (1) to quantify the difference in ^{32}P uptake by coconut palms interplanted with dicot multipurpose trees during a later stage in the rotation, (2) to evaluate the effects of differing levels of resource availability and planting geometry of interplanted dicot trees on ^{32}P recovery by the coconut palms, (3) to examine how variations in lateral distance from the treated palms and root growth traits of interplanted dicot trees influence recovery of ^{32}P by neighbouring dicot trees, and (4) to evaluate the impact of interplanted dicot tree species, their planting geometry, and soil fertility levels on yield and foliar NPK levels of coconut palms.

Materials and Methods

The field experiment was established in June 1992 in an existing commercial coconut plantation at Vellanikkara, Kerala (10°13′ N and 76°13′ E at an elevation of 40 m above sea level). It involved three dicot multipurpose trees (*Ailanthus triphysa, Grevillea robusta*, and *Vateria indica*) having divergent growth habits/crown architecture interplanted in the 14-year-old coconut plantation (i.e. one dicot tree species per plot), following two planting geometries (single-hedge and double-hedge systems), besides sole coconut stands as control. Incidentally, coconut was planted in this area in 1978 using 1-year-old hybrid seedlings (Lacadive Ordinary × Gangabondam) at 7.5 × 7.5 m spacing (see Kumar et al. 1999 for a description on location, soil, and the experimental set-up). Briefly summarized, the site experiences a warm humid climate having mean annual rainfall over 2800 mm, with most of the rainfall received during the southwest monsoon season (June–August) with a secondary peak during September–October (northeast monsoon). The mean maximum temperature ranges from 28.6 °C (July) to 36.5 °C (March) and the mean minimum temperature from 22.2 °C (December) to 24.7 °C (May). The soil at the experimental site is a Typic Plinthustult – Vellanikkara series midland laterite (ustic moisture regimes and isohyperthermic temperature regimes). The single row system involved one row of dicot trees in the middle of two adjacent coconut rows in both directions (Figure 11.1), and the double-row system involved two rows of the dicots in the middle of two adjacent rows of coconut palms following an east–west orientation (Figure 11.2). The dicot tree population density in the interspaces (i.e. one or two rows in single and double row systems respectively) was kept constant at 72 trees per plot (1800 trees ha^{-1}) for both treatments. Tree-to-tree (dicot) distance was 2 m uniformly; and row spacing in the double row planting system (between the paired rows) was 1 m. There were 21 experimental plots of size 20 × 20 m. Each plot consisted of nine coconut palms and involved three replicate blocks. The reporting period corresponds to dicot tree age of 8 years, when an experimental NPK gradient (high, medium, and low fertility) was created to amplify site differences (between blocks) in soil fertility. This was accomplished by fertilizing the coconut palms in different blocks with differential doses of NPK, organic manure, and lime (Table 11.1). Incidentally, the "high" and "medium"

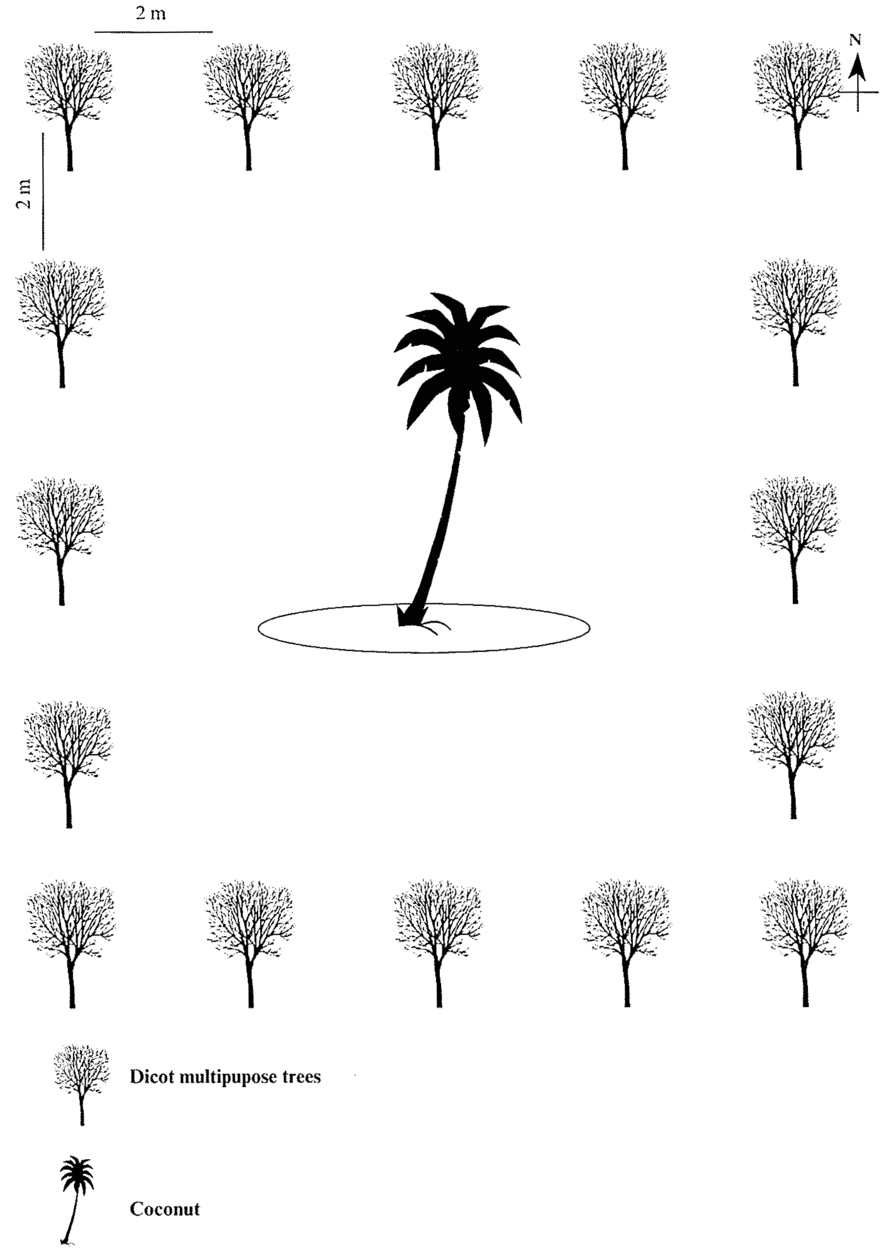

Figure 11.1 Schematic diagram showing an experimental unit involving coconut palms and dicot multipurpose trees in single hedge system (trees are drawn not to scale). The palms planted at 7.5 m × 7.5 m were 22 years and the dicot trees 8 years old at the time of the present experimentation

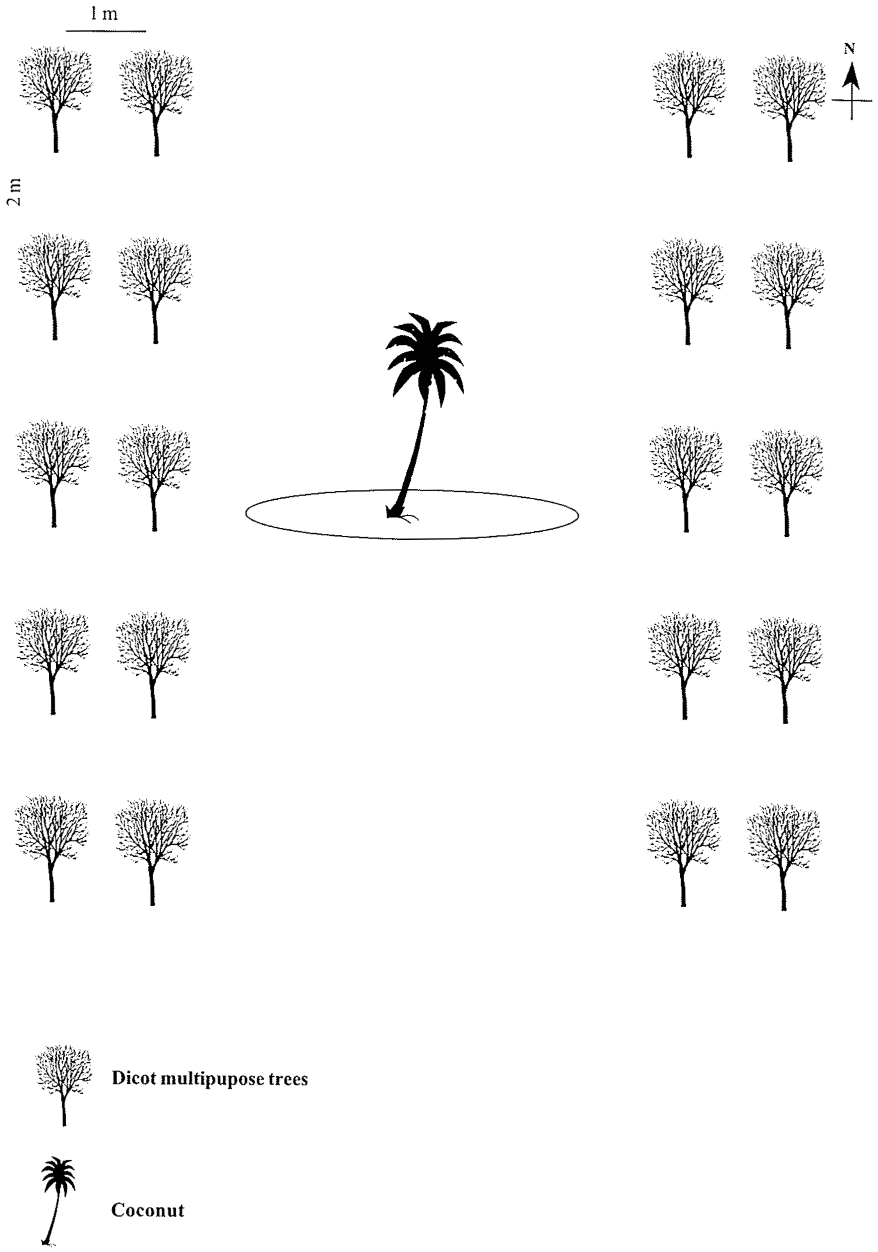

Figure 11.2 Schematic diagram showing an experimental unit involving coconut palms and dicot multipurpose trees in double hedge system. The palms planted at 7.5 × 7.5 m were 22 years and the dicot trees 8 years old at the time of the present experimentation

Table 11.1 Rates of fertilizers and manures applied to the coconut palms in different experimental blocks (Kerala, India) to create a gradient in soil nutrient availability

	Fertilizers and manures (kg/palm/year)[a]				
Block designation	N	P_2O_5	K_2O	Organic manure	Lime
High fertility	0.50	0.32	1.2	25	1
Medium fertility	0.34	0.17	0.68	15	0.5
Low fertility	0	0	0	0	0

[a] "High" and "medium" fertility levels correspond to the nutritional regimes under "good" and "average" systems of crop management according to local recommendations (KAU, 2002).

fertility regimes correspond to the recommended doses of fertilizers for "good" and "average" systems of crop management respectively, according to local crop management recommendations (KAU, 2002). No fertilizers/manures were incorporated in the "low" fertility block.

Tracer Studies on Root Interactions

The nature and extent of root competition between coconut palms and the neighbouring dicot trees were studied by soil-injection of ^{32}P into the root zone of coconut and quantifying ^{32}P absorption through radio-assay of not only the treated coconut palms but also the dicot trees surrounding it. Central palm in each plot was selected for ^{32}P application. The distance between the nearest two palms selected for ^{32}P treatment was at least 30 m (four rows of coconut palms in between) to avoid any cross-feeding between treated palms. Furthermore, to ensure effective absorption of ^{32}P by the palms, the radioactivity was applied to 36 holes per palm basin (Figure 11.3) corresponding to the combinations of four lateral distances (50, 100, 150, and 200 cm) and three depths (30, 60, and 90 cm). Regarding the depth of application, although most (80%) of the coconut root activity may be concentrated up to 60 cm depth and 200 cm radial distance under sole crop situations (Wahid, 2000), in this experiment, our idea has been to "pack" the entire root zone of the palms with the radio-label, as far as possible. Furthermore, in intercropping systems involving woody perennials such as these, due to root system plasticity, it is probable that trees may become more deep-rooted compared to monospecific stands (see Divakara et al. 2001), thus justifying the inclusion of the deeper 90 cm layer for ^{32}P application.

Thirty six equi-spaced holes were drilled to the required depth and lateral distance in four concentric circles (Figure 11.3) around each palm, using a soil auger of 2.5 cm diameter. PVC access tubes were installed in the holes with 10–15 cm of the tube protruding above the soil surface, which was capped to prevent the entry of rainwater. ^{32}P solution at the rate of 5 ml at a carrier level of 1000 ppm P was applied into each access tube on October 30, 2000, using a dispenser designed for the purpose (Wahid et al. 1988). The time of ^{32}P injection (October – just after the cessation of the northeast monsoon rains) was deliberately chosen to ensure

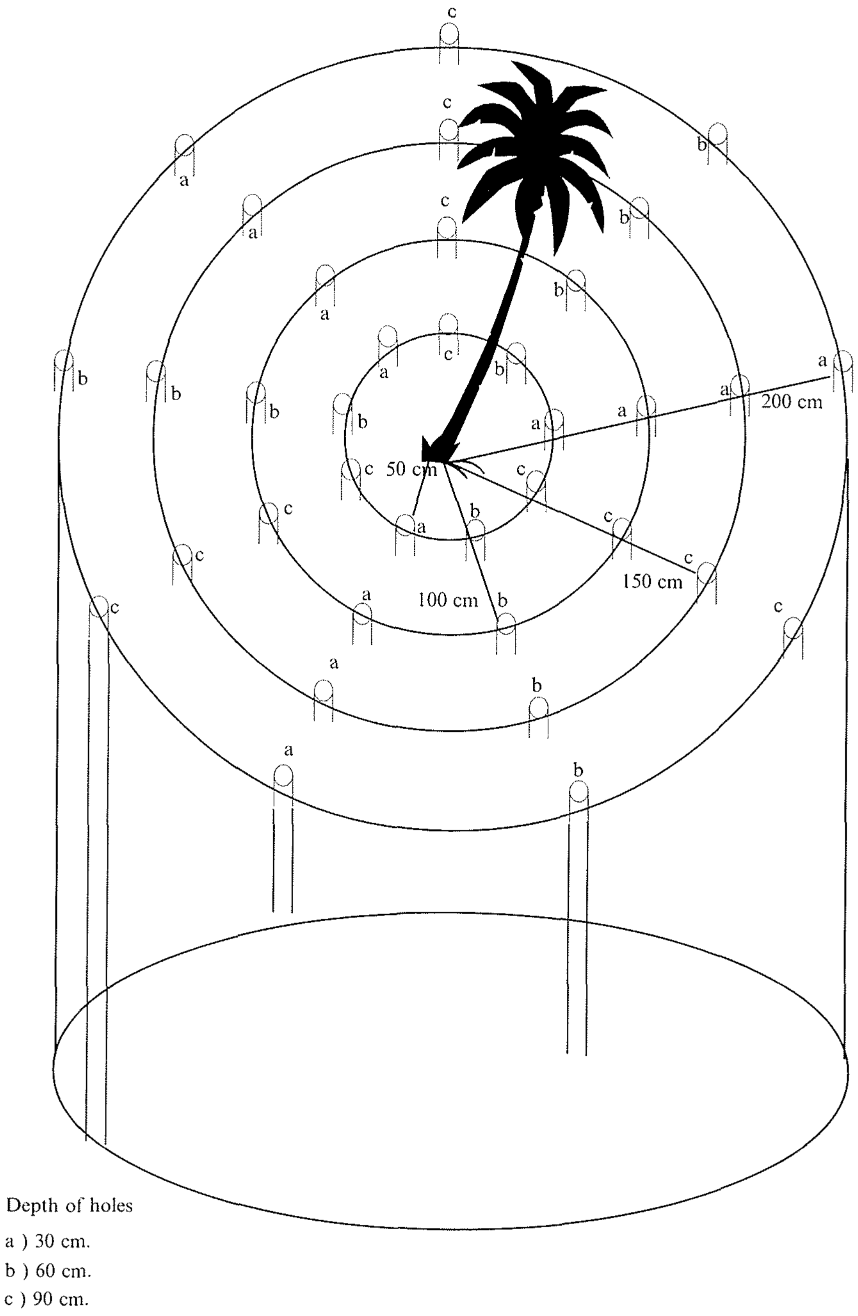

Figure 11.3 Lay out plan for ^{32}P application in the coconut basin showing the locations of holes for ^{32}P injection

adequate soil moisture availability and to avoid periods of heavy rainfall. Indeed, many previous experiments involving ^{32}P (e.g. George et al. 1996; Thomas et al. 1998; Kumar et al. 1999) have shown that nutrient uptake by woody perennials may be satisfactory, if soil moisture is not limiting. The total radioactivity applied to each palm in this study was 111 MBq (elemental ^{32}P in HCl). After dispensing, the residual activity remaining inside the access tube was washed down with a jet of about 15 ml water. Carrier in the ^{32}P solution was included to minimize soil fixation of the applied radio-label (IAEA 1975), and it was over and above the fertilizers applied in June, 2000 (Table 11.1).

Leaf Sampling and Radio-assay

Leaves from treated coconut palms and neighbouring dicot trees were sampled for radio-assay at 15 and 30 days after application of ^{32}P. Because these measurements were correlated, we report only the 15th day data here. For coconut, the sixth fully opened leaf was selected and three leaflets from either side of the midrib from the middle portion were sampled (IAEA, 1975). For dicot trees, the most recently matured leaves were selected. Leaf samples of all neighbouring trees were sampled but those situated at similar distances from the treated palms (on opposite sides) were pooled to obtain composite samples (Figures 11.1 and 10.2). Samples were dried at 70 °C and radio-assayed by Cerenkov counting technique (Wahid et al. 1985). The method consisted of wet digestion of 1 g of dried leaf sample using diacid mixture (HNO_3 and $HClO_4$). The digest was transferred to counting vials and made up to 20 ml with water and counted in a liquid scintillation counter (Wallac, 1409, Pharmacia, Finland). The count rates were expressed as cpm (counts per minute per gram leaf dry weight).

Soil Sampling

Soil samples were collected from the basins of the central palms in all plots on 19 September 2000, nearly 4 months after the application of manures and fertilizers. Samples were collected from the surface layer (0–15 cm) at three random points in each plot and mixed thoroughly to form a composite sample, from which three subsamples were drawn. The samples were air-dried and passed through a 2 mm sieve and analyzed for soil pH, organic C, N, P, and K following standard procedures and expressed on an oven dry basis.

Root Count of Dicot Trees

To evaluate the root distribution pattern of the focal dicot trees, the root systems of 27 border trees (nine each per species randomly selected from three different size

classes representing the range of trees) were partially excavated using the modified logarithmic spiral trench method (see Kumar and Divakara (2001) for methodological details). The data on rooting intensity (number per m^2) were regressed on distance from the base of the tree and prediction equations were developed (details to be presented elsewhere), which were used for estimating rooting intensity of the dicot trees at 4 and 5 m away from the coconut trunk.

Coconut Yield, Foliar Nutrient Concentrations and Dicot Tree Growth Rates

The impact of interplanted dicot trees on nut yield of all palms in each plot was evaluated from 1991 to 2000; only data corresponding to the year following soil fertility manipulation are included here. In addition, duplicate samples of coconut leaves collected on 14 November 2000 were analyzed for N, P, and K. To assess the growth response of tree species, tree height and stem diameter at breast height (1.37 m) were also recorded.

Statistical Analysis

Before statistical analyses, the cpm values were corrected for background as well as decay and subjected to $\log_{10}$ transformation to meet the assumptions of normality and homogeneity of group variance. Analysis of variance and LSD Tests were performed on the data on ^{32}P absorption by coconut palms. To characterize ^{32}P absorption by neighbouring plants at different lateral distances from treated coconut palm, the MPT foliar ^{32}P counts were regressed on distance from the coconut palm. Owing to inherent variations in biomass accumulation rates and the consequential differences in ^{32}P counts of the dicot MPTs, only within species comparisons were made. Data on soil characteristics, plant nutrient levels, and nut yield of palms were also analyzed using ANOVA followed by LSD Test.

Results and Discussion

^{32}P Recovery by Coconut Palms, Foliar Nutrient Levels, and Nut Yield

As expected, the "high" and "medium" fertility blocks showed higher ($p < 0.01$) soil N and P levels than the low fertility block; K levels were, however, inconsistent (Table 11.2). Despite this, differences in foliar recovery of ^{32}P by coconut or their foliar NPK levels were not significant (Table 11.3). Nut yield of the palms

Table 11.2 Soil physico-chemical properties of the experimental blocks involving coconut and multipurpose trees in Kerala, India

Blocks	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Available K (mg kg^{-1})	pH
Block effects (soil fertility)					
High fertility	1.80	0.187^{a}	44.1^{a}	224.4^{a}	5.47^{a}
Medium fertility	1.88	0.185^{a}	25.9^{b}	187.1^{b}	5.19^{a}
Low fertility	1.84	0.160^{b}	11.7^{c}	$205.8^{a,b}$	5.05^{b}
Significance	NS	<0.01	<0.01	<0.01	<0.01

Means followed by the same superscript do not differ significantly.

Table 11.3 Mean ^{32}P uptake and nut yield of 22-year-old coconut palms as affected by interplanted dicot multipurpose trees (8-year-old), planting geometry and soil fertility levels

Treatments	^{32}P Counts min^{-1} g leaf dry weight^{-1} ($\log_{10}$ transformed values)	Nutrient concentration of coconut leaves (%)			Nut yield (number palm^{-1} year^{-1}) [Sept 2000 to Aug 2001]
		N	P	K	
Interplanted dicot Species					
Coconut + *Vateria indica*	2.30 (566)	1.82	0.12	1.32	44.7
Coconut + *Ailanthus triphysa*	2.22 (412)	1.79	0.13	1.45	36.3
Coconut + *Grevillea robusta*	2.16 (187)	1.77	0.14	1.22	53.5
Control (coconut sole crop)	2.09 (125)	1.8	0.13	1.09	57
Significance (dicot species)	NS	NS	NS	NS	NS
Control vs. rest	NS	NS	NS	NS	NS
Planting geometry					
Single hedge	2.35 (514)	1.87	0.13	1.32	44.6
Double hedge	2.10 (263)	1.71	0.13	1.34	45.1
Significance	NS	NS	NS	NS	NS
Species × planting geometry interaction	NS	NS	NS	NS	NS
Block effects (soil fertility)					
High fertility	2.88 (762)	1.91	0.11^{a}	1.34	50.7
Medium fertility	2.14 (139)	1.78	0.13^{a}	1.30	43.7
Low fertility	2.17 (151)	1.71	0.15^{b}	1.25	45.3
Significance	NS	NS	<0.05	NS	NS

Figures in parenthesis indicate re-transformed values; NS – not significant.
Means followed by the same superscript do not differ significantly.

also showed no statistically significant differences, regardless of variations in interplanted dicot tree species, planting geometry, and/or soil fertility changes along the gradient. Likewise, soil NPK and organic C levels revealed no marked variability among the dicot tree species and their planting geometry (data not presented). Furthermore, a comparison of the data (control vs. rest) in Table 11.3 suggests that even the presence or absence of dicot trees in the system had no significant influence on ^{32}P recovery, foliar NPK levels and nut yield of the

palms. A plausible explanation for this consistently non-significant response is the non-competitive nature of the interplanted trees in this experimental polycultural system for belowground resources. Notably, the lack of competition extends for a considerable part of the 12–15 year rotation of the intercropped trees (i.e. at least up to 8 years after planting). This is presumably because of the greater resource acquisition ability of coconut palms owing to their earlier establishment compared to the dicot trees (resource pre-emption as postulated by Wiener [1990], but see Wedin and Tilman, 1993).

In addition, our data do not support the hypothesis that root competition may be greater under resource-rich or under resource-poor situations. In particular, if the soil nutrient availability is moderate to high (see Table 11.2: even the "low fertility block" had fair amount of nutrients), competitive interactions are unlikely. In earlier studies at an adjacent site, Thomas et al. (1998) also found that woody perennials did not significantly alter the nutrient uptake pattern (^{32}P) of herbaceous intercrops, when soil fertility was moderate to high. This is, however, not consistent with some of the previous reports concerning root competition in natural ecosystems. For instance, Wilson and Tilman (1993) indicated that belowground competition for a temperate perennial grass (*Schizachyrium scoparium*) may be most intense in plots with lowest N availability and decreased significantly with increasing N availability; Keddy (1989), however, proposed an opposing view. Thus, in managed land-use systems such as homegardens, nutrient addition is unlikely to bring about significant changes in competition for P, regardless of variations in inherent soil fertility. This may be partly because of the selective stimulation/early establishment of the target species (e.g. coconut), unlike in the natural systems studied by the authors mentioned above where simultaneous colonization by competing species and/or more complete exploitation of the site nutrient resources are probable.

Dynamics of Inter-specific Competitive Interactions

A comparison of the data on ^{32}P uptake by coconut palms at the previous stage of observation (i.e. 3 years after interplanting) show that despite overall differences between treeless control (dicot) and interplanted dicot trees being not significant, variations among the dicot species were profound (Kumar et al. 1999). Furthermore, ^{32}P recovery of coconut at that stage was lower in the *V. indica* and *A. triphysa* intercropped plots compared to that of *G. robusta*. At the present stage of observation, however, *V. indica* and *A. triphysa* under the "high fertility" level, showed substantially higher ^{32}P counts (Table 11.3). Yet, these differences (including interaction effects) were not statistically significant, presumably because of the high coefficient of variation in some treatments, which in turn, reflects heterogeneity in root distribution of individual trees within the application zone.

The differential pattern of ^{32}P uptake by coconut in the intercropped plots between 3 years and 8 years probably reflects the dynamic nature of root interactions. As the intercropped trees approach maturity, their root systems (tap) probably became more stratified in relation to the fibrous root systems of coconut and in that process the initial apparently negative effect of certain species (Kumar et al. 1999) may be transformed into a more positive impact. At 8 years after planting dicot trees, therefore, both *V. indica* and *A. triphysa* seemed to stimulate greater ^{32}P recovery by coconut palms (with ^{32}P counts of 566 and 412 min^{-1} g^{-1} leaf fresh weight as opposed to ^{32}P counts of 187 for *G. robusta* and 125 min^{-1} g^{-1} leaf fresh weight for sole coconut; Table 11.3). This effect is seemingly more pronounced in the "high fertility block" (e.g. ^{32}P counts of 762 min^{-1} g^{-1} leaf fresh weight as opposed to 139 and 151, respectively for the "medium" and "low fertility" blocks; Table 11.3). Yet, the differences were not statistically significant, presumably because of the high coefficient of variations for isotope counts, which incidentally is a general problem in such studies (sensu Rowe and Cadisch, 2002). Nonetheless, in view of the large differences, it can probably be inferred as a potential benefit of intercropping on nutrient uptake by coconut under "good management." A plausible explanation for this is the high root activity of coconut palms especially in the "high fertility blocks." Although ^{32}P uptake can be regarded as a direct index of root activity (Wahid, 2000), our interpretations are limited by the non-availability of coconut rooting intensity data under different fertility/management regimes.

Furthermore, in mixed species systems especially those involving two or more woody perennials, the root architectural pattern may be modified by the proximity of other tree components. For instance, in the coconut + dicot tree system presently studied, certain dicot species tend to develop deeper root systems when grown in association with monocots (e.g. *V. indica*; Table 11.4); while others may form more expanding/overlapping root systems (e.g. *A. triphysa*). The resultant higher root-length density in the subsoil, nevertheless, reduces nutrient leaching (safety-net hypothesis; Rowe et al. 1999; Divakara et al. 2001). This is of particular relevance in the high rainfall zones of Kerala (mean annual rainfall > 2600 mm at this experimental site), where the potential for leaching losses are quite high. Earlier, Kumar and Divakara (2001) reported that in bamboo-based multi-strata systems of Kerala, India, ^{32}P uptake from the subsoil was greater when the bamboo clumps (*Bambusa arundinacea*) and dicot trees (*Tectona grandis* and *Vateria indica*) were close to one another, implying greater subsoil root activity.

Table 11.4 Mean rooting intensity of 8-year-old fast growing multipurpose trees at different depth intervals and lateral distances from the base of the coconut palms (Estimated using the regression equations in Gowda, 2002.)

	Vateria indica		*Ailanthus triphysa*		*Grevillea robusta*	
	Number of roots m^{-2} at 4m and 5m lateral distance from coconut palms					
Soil depth (cm)	4	5	4	5	4	5
0 — 10	364 (8.4)	158 (3.6)	499 (6.0)	282 (3.5)	333 (9.5)	147 (4.2)
10 — 20	351 (8.1)	144 (3.3)	380 (4.7)	249 (3.1)	364 (10.4)	127 (3.6)
20 — 30	318 (7.3)	122 (2.8)	300 (3.7)	220 (2.7)	231 (6.6)	102 (2.9)
30 — 40	264 (6.1)	96 (2.1)	209 (2.6)	180 (2.2)	204 (5.8)	78 (2.2)
40 — 50	182 (4.2)	118 (2.7)	87 (1.0)	96 (1.2)	84 (2.4)	38 (1.0)

Parenthetical values are percentages

^{32}P Recovery by Neighbouring Multipurpose Trees

Interplanted dicot trees absorbed considerable quantities of the radio-label applied to the coconut palm. As normal, ^{32}P uptake by the interplanted trees declined log-linearly with distance from the palms in most cases (Figure 11.4). This decline in dicot tree leaf ^{32}P recovery with distance from the ^{32}P application point indicates the range of "scavenging" by the neighbourhood/intercropped trees. Differences in species, soil fertility regimes and planting geometry seemed to alter this pattern only modestly. Yet, *A. triphysa* and *G. robusta* under "medium fertility" and double hedge row system, besides *G. robusta* under "high fertility" and single hedge system showed an increasing trend with distance from the treated palms, which is intriguing. This is likely to have resulted from the heterogeneity in dicot tree root distribution. The present study, however, is incapable of making further generalizations in this respect, as data on root distribution pattern under differing planning geometry/soil fertility levels are not available.

Recovery of ^{32}P applied to the coconut palm by the interplanted trees implies that both coconut palms and the dicot trees draw upon from the same nutrient pool. As we could not detect any negative impact of intercropping dicot trees on ^{32}P recovery by the coconuts, it is perhaps reasonable to assume that the interplanted trees absorbed that fraction of the ^{32}P pool which is not utilized by the palms. This, in turn, suggests that dicot tree intercropping in coconut gardens may lead to complementary interactions and, in particular, enhanced efficiency in the utilization of applied nutrients. This can be further rationalized as follows.

Although inter-specific differences among competing species in belowground resource acquisition rates in mixed species managed land-use systems are probable initially (i.e. when the trees are growing actively), once canopy closure is attained, because of a positive feedback between growth and nutrient cycling, the dominant forms of plant interactions may be either neutralism (e.g. *G. robusta*) or complementarity (e.g. *V. indica* and *A. triphysa*). Therefore, in mixed coconut palm–dicot tree systems, there is greater spatial complementarity in belowground resource use. Within reasonable limits, such complementary interactions among woody perennials are independent of site fertility too. This is consistent with the findings of Wilson and Tilman (1991) who found that in three dominant temperate grasses, the intensity of competition, measured as the suppression of transplants by neighbours, did not vary significantly with nitrogen availability. Although many previous workers (George et al. 1996; Thomas et al. 1998; Nissen et al. 1999) have cited evidences in support of complementary interactions in woody perennials + herbaceous crop systems, the present results should not be extrapolated to other mixed species systems, especially those involving trees and intolerant herbaceous components, or to tree-based systems in which all the tree components are established simultaneously.

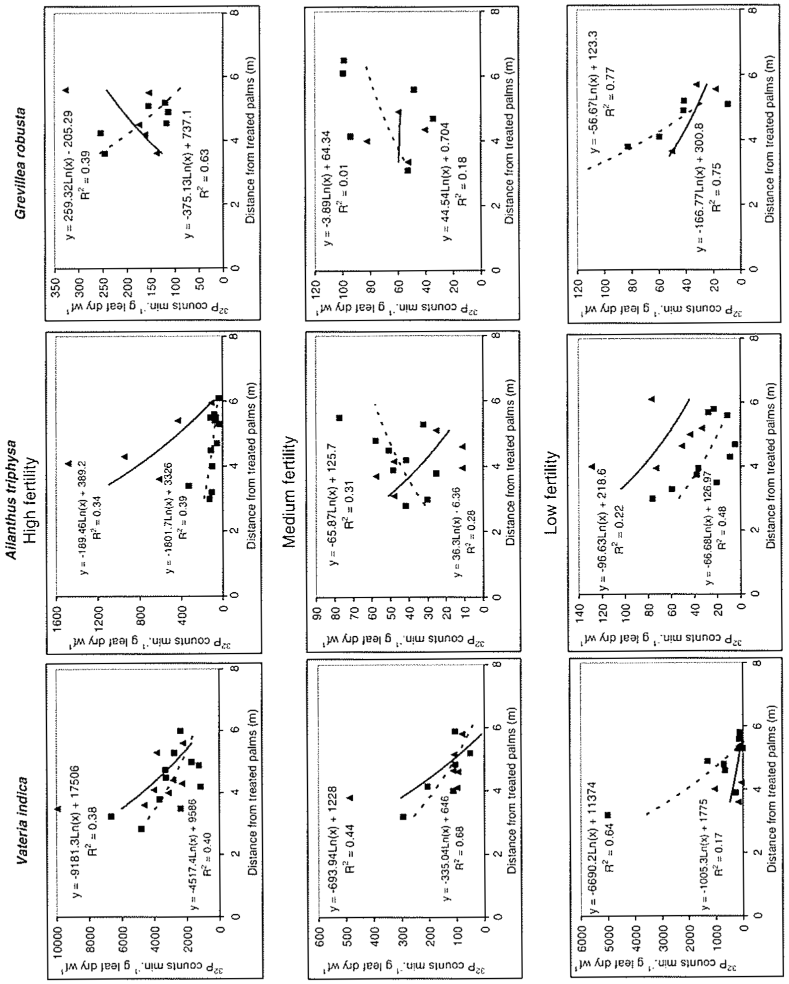

Figure 11.4 ^{32}P uptake by three fast growing multipurpose trees interplanted in a mature coconut plantation at 15 days after application of the label as influenced by distance from the treated coconut palms, resource availability and planting geometry (triangle and solid lines represent single hedge planting while squares and dotted lines signify double hedge planting with equations given in that sequence) in Kerala, India for "good", "average" and "poor" management conditions.

Tree Attributes on Interactions

Height and radial growth differences of interplanted dicot trees were significant ($p < 0.01$) with *A. triphysa* registering faster height and radial growth than other trees (Figure 11.5). Our root excavation data on border trees in this experimental setup indicate that lateral root spread is considerably variable (163–469 cm; Gowda 2002). *A. triphysa* has had far more roots in the 4–5 m lateral distance zone from the coconut palms than other species and *V. indica* is particularly deep rooted (i.e. relatively higher rooting intensity in the deeper layers; Table 11.4). The rooting intensity data may thus partially illustrate the observed variations in ^{32}P uptake patterns Ruhigwa et al. (1992) also noted considerable variations in rooting characteristics of MPTs. That is, roots of some hedgerow intercropping tree species (*Alchornea cordifolia* and *Senna* (*Cassia*) *siamea*) were evenly distributed over the crop alley, while those of *Acioa* (*Dactyladenia*) *barteri* were concentrated close to the tree base. Consistent with this, Rowe et al. (2001) found that in Sumatra *Peltophorum dasyrrachis* trees did not compete with crop plants for topsoil N although *Gliricidia sepium* exhibited a tendency to strongly compete with intercropped maize during early crop establishment.

Overall, root competitiveness in managed land-use systems is variable and the magnitude is probably controlled by species attributes such as root architecture and/or tree growth traits. The chances of significant root competition in experimental

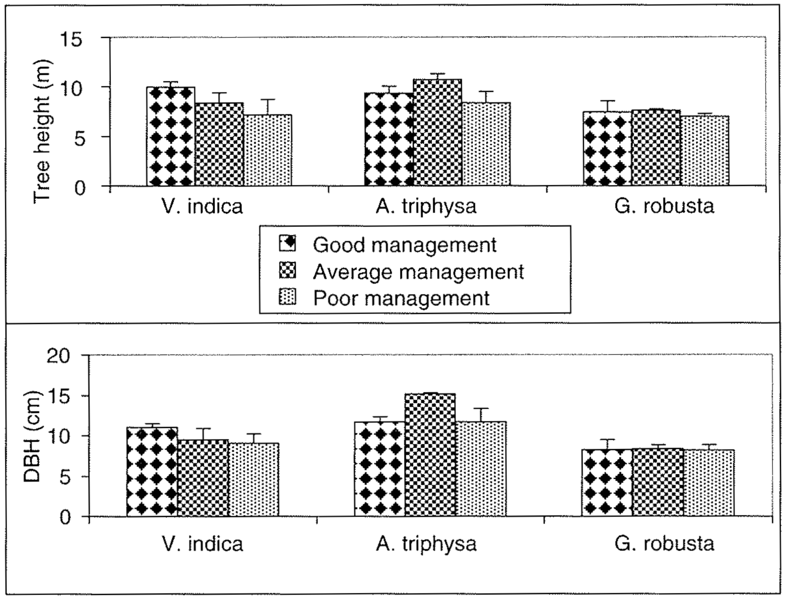

Figure 11.5 Height and radial growth of three fast growing multipurpose trees interplanted in a mature coconut plantation as influenced by distance from the treated coconut palms and planting geometry in soil fertility gradient in Kerala, India (Error bars are standard deviations)

systems such as these where the intercrop follows the main crop after 8 years are, however, seemingly remote. Conversely, if there is a considerable overlap among the root systems of the interacting species, then complementarity may possibly switch to competition. This probably implies the promiscuous nature of root interactions in land-use systems involving woody perennials, and detailed studies involving a disparate range of multipurpose trees are necessary to designate species with complementary root interactions similar to that of *V. indica* and *A. triphysa*.

The results of the present study, however, may be interpreted with caution. Our ^{32}P results are for a single season and that the augmented soil fertility gradient was in existence for just about 4 months before the ^{32}P placement, albeit some block differences in soil fertility levels were in existence since the beginning of the study (authors' observation). For polycultural systems involving woody perennials, long-term studies with clear fertility gradients are probably imperative. Interactions between above- and belowground competition are also plausible at about canopy closure (see Wilson and Tilman, 1991). Yet in our study, the lack of significant variations in nut yield and ^{32}P recovery by coconut palms with and without intercropped multipurpose trees suggests that both above- and belowground competition for site resources were modest. However, if the dicot tree canopy rises above or even to the same level as that of the coconut crowns (overlapping), competition for light could become a potential limiting factor and that the effects of competition for light and nutrients may interact (see Jackson and Caldwell, 1992). Such inter-specific competition perhaps will be of greater magnitude on the relatively more productive sites, as suggested by Grime (1973). However, in the present experiment, the canopies of coconut and the associated dicot tree components were separated (until now) both vertically (taller in view of the greater palm age) and horizontally in view of the specific planting geometries adopted and/or differences in age/crown architectures/growth habits.

Conclusions

Although many workers addressed the question of whether the effects of root competition are more severe on nutrient-poor or nutrient-rich soils, this paradox still remains unresolved. Indeed, most previous studies represent natural ecosystems and reports on the nature and magnitude of inter-specific competition in managed mixed species systems involving woody perennials in particular are scarce. Our results suggest a general non-dependence of belowground competition, measured as coconut ^{32}P uptake, on interplanted dicot species and soil fertility variations caused by adding moderate quantities of nutrients (e.g. 89, 57, and 214 kg N, P_2O_5, and K_2O ha^{-1} in the "high fertility block" and 61, 30, and 121 kg N, P_2O_5, and K_2O ha^{-1} for the "medium fertility" block). While the soil fertility variations control the potential productivity of a site, it has perhaps little or no influence on the magnitude of inter-specific root competition in such systems. This generalization, however, is limited to intercropping systems involving two or more woody perennials and where the potentially competing woody perennial intercrops follow the main crop after it has become well established.

The study was successful in quantifying ^{32}P uptake from the coconut root zone both by the treated palms as well as neighbouring dicot trees after canopy closure. ^{32}P recovery following soil injection of the label in the effective root zone of coconut palms did not show any direct evidence that root competition occurred in these experimental communities. It also provides insights into the distribution of root activity in mixed species production systems involving two or more woody perennial components, and its influence on the degree of complementarity in resource partitioning. There was a non-significant tendency for *V. indica* and *A. triphysa* to enhance ^{32}P uptake by coconut palms under high fertility levels. A plausible explanation for the lack of significant variations in ^{32}P uptake of coconuts is perhaps the spatially discrete (vertically and horizontally) root systems developed by these dicot species and the coconut palms. There could, however, be species-dependent variations. In addition, the interplanted dicot trees absorbed substantial ^{32}P label from the coconut rhizosphere, which otherwise would probably have remained unutilized by the main crop. By extension, in homegardens where tree components are closely integrated, there is a substantial potential for "capturing" the lower leaching nutrients. And in general, incorporation of woody perennials in land-use systems enhances the nutrient use efficiency, which is generally regarded as very low for most agricultural soils. Growing trees in close proximity also has advantages such as more stratified component root systems, higher rooting density, reduced nutrient leaching and better recycling of subsoil nutrients.

Acknowledgements This research forms part of the MSc (Forestry) thesis submitted to Kerala Agricultural University, Thrissur, India, by the first author. Assistance in radioisotope procurement, application and analysis by Professor (Mrs.) N.V. Kamalam and Dr. P. Sureshkumar of the Radioisotope laboratory, Kerala Agricultural University are gratefully acknowledged.

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Chapter 12

Establishment of *Cordia dodecandra* A.DC. with *Bixa orellana* L. on Calcareous Soils in Yucatán, Mexico

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Introduction

Due to the predominance of *Agave fourcroydes* Lem. plantations in northern Yucatan during the last 150 years, the economic importance of trees outside of the traditional homegardens has largely been neglected. Few farmers in northern Yucatan use native trees to supply multiple services and goods such as shade and shelter for animals, food, medicines, and timber for construction and furniture, outside their homegardens. After the abandonment of sisal production in the 'henequen area', plantation lands were assigned to the communities (Nickel 1995). The present challenge is to develop agroforestry systems for the recultivation of the plantation areas that improve livelihoods, and that are adapted to the climatic and soil conditions of northern Yucatan. A number of native tree species are promising candidates as tree components for such recultivation schemes. To guarantee survival and growth of seedlings, suitable species have to be adapted to the seasonally hot and dry environmental conditions of the northern peninsula.

The native multi-purpose tree *Cordia dodecandra* A.DC. (Siricote) (Boraginaceae) was reported to establish and grow well (H. Flachsenberg, 2002, personal e-mail communication, from Tegucigalpa, Honduras). *C. dodecandra* produces timber with higher

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export market value than mahogany (*Swietenia macrophylla* King). Fruits of Siricote are sold for the traditional dessert 'dulce de Siricote'. Leaves serve as a substitute for sandpaper, and the bark is used for medicinal purposes. Due to the roughness of the leaves, goats do not harm the seedlings, and eventually benefit from shade and shelter provided by the tree. *C. dodecandra* can be combined with corn or other annual or perennial crops as well as with small ruminants (Vlek et al. 2004). Another traditional Mayan homegarden species is the food colorant bush *Bixa orellana* L. (Annatto). *B. orellana* was planted successfully in agroforestry plots in southern Quintana Roo by the World Agroforestry Centre (ICRAF) (J. Haggar, 2002, personal e-mail communication, from Managua, Nicaragua).

It is difficult to give recommendations for successful management of tree and crop plantations in northern Yucatan, because of the high spatial variability of soils, typically a mix of black Leptosols and red Cambisols. The predominant soils of the northern peninsula are stony and shallow, with depths of less than 20 cm (Reuter et al. 1998). With predominantly high evaporation and a 4-month drought period, water availability is important for growth and survival of plants. Hurricane occurrence presents a threat to planted seedlings and trees.

In September 2002, hurricane Isidore reduced tree cover in some communities by up to 70%, and farmers are now becoming interested in reestablishing lost tree cover and in using native tree species. So far, farmers in the northern peninsula rarely established small-scale plantations of indigenous multi-purpose trees to obtain additional income. In contrast, communities in southern Yucatan, where climatic and soil conditions are more favorable, are well aware of the commercial value of timber of indigenous species. Southern farmers have established agroforestry plots and small-scale plantations with species such as *C. dodecandra* on their own account. Farmers in northern Yucatan still need detailed information on the adaptability and successful management of indigenous species. Gaining experience with the establishment of native tree species is the first step to create economically and ecologically sustainable agroforestry systems. The present lack of knowledge on how these indigenous tree species develop on the dominant soil types of northern Yucatan has to be addressed (CONAFOR 2004). The objective of the present study was to determine the suitability of *C. dodecandra* and *B. orellana* for the establishment of agroforestry schemes on stony soils with limiting precipitation, and to identify irrigation options for the establishment of seedlings.

Materials and Methods

Site and Soil Description

The area of abandoned plantations of *A. fourcroydes*, the 'henequen area', is situated in the northern part of the Yucatan Peninsula, in the State of Yucatan, Mexico. The area is a nearly flat calcareous plain, formed from tertiary limestone of marine origin, with an altitude of 0–20 m a.s.l. (Seele 2001) and scattered convex mounds of often less than 3 m height with gentle slopes. Shallowness and exposed limestone characterize the highly heterogeneous soils (Duch 1988). The Mayan soil classification of the Yucatan Peninsula distinguishes between soil classes according to their position in the micro-relief, stoniness, and color (Estrada Medina 2000). In the experimental area, red Kankab soils on plains were classified as Cambisol (equivalent soil order in US Soil Taxonomy is Inceptisol) and black Tsekel soils on mounds as Leptosol (equivalent soil order in US Soil Taxonomy is Entisol). At all three experimental sites, red Kankab and black Tsekel soils were present in about equal proportions. Black Tsekels are very shallow, have a high percentage of rock outcrops and stones and low water retention capacity. On plain terrain, red-colored, less stony Kankabs with lower organic matter content are found. Their subsoil consists of limestone that may inhibit root development. Their depth varies between 20 and 100 cm. Kankab soils have a moderate water retention capacity (Estrada Medina 2000; Reuter et al. 1998; Duch 1995, 1988). Soils were sampled at 30 randomly distributed spots, each on black Leptosol to a depth of 30 cm and on red Cambisol to a depth of 20 cm. The pH of each sample was measured in H_2O and in 0.01 M Calcium ($CaCl_2$) solution (Scheffer and Schachtschabel 1992). In the experimental area, the pH in $CaCl_2$ of the Cambisol was 7.3, of the Leptosol 7.6. The pH in water of the Cambisol was 7.9, of the Leptosol 8.1.

The experimental plots were situated on three research sites about 5 km from the Veterinary Faculty (FMVZ) of the Autonomous University of Yucatan in X'matkuil, 15.5 km South of Mérida, at latitude 20.58′ N and longitude 89.38′ W. On all three sites, wells provided water for irrigation during the dry season. Historically, site 2 was part of a sisal plantation. For about 10 years, it was overgrown by secondary vegetation of about 5–8 m height. In late 1998, the site was slashed and burned. The history of site 3 was similar. Most of site 1 was cleared from fallow vegetation by slash-and-burn in 1999. A sub-site of site 1 was only cleared in 2001. On all three sites, scattered patches had been sown with corn mixtures of corn and Leguminosae (*Vigna* and *Mucuna species*) during the past season, while most of the area was covered with regrowth of secondary vegetation of 1.5–2 m height. Some low secondary vegetation bordered the experimental plots. In contrast to other parts of the area, the sub-site on site 1 was surrounded on three sides by mounds that were covered with tall, older secondary vegetation (Figure 12.1a).

The climate in Mérida, Yucatan, 15 km from our experimental sites, is hot semiarid with distinct rainy and dry season. Long-term mean annual temperature is 26.8°C, with the lowest mean monthly temperatures in January. The peak of the dry season in the Northern Yucatan Peninsula is from April to May, with long-term mean maximum monthly temperatures of up to 40°C in May recorded for Mérida. Long-term mean annual precipitation in Mérida is 984.4 mm. More than 80% of the annual precipitation falls between May and October. Long-term mean maximum monthly precipitation in Mérida is 187 mm in September, equivalent to 19% of the total annual precipitation. In November and December, rains accompany the winds called *nortes*. Minimum precipitation falls between January and May (Orellana 1997; Duch 1988). Hurricane season is from September to October. Natural vegetation is described as deciduous thorny scrub forest (Wilson 1980).

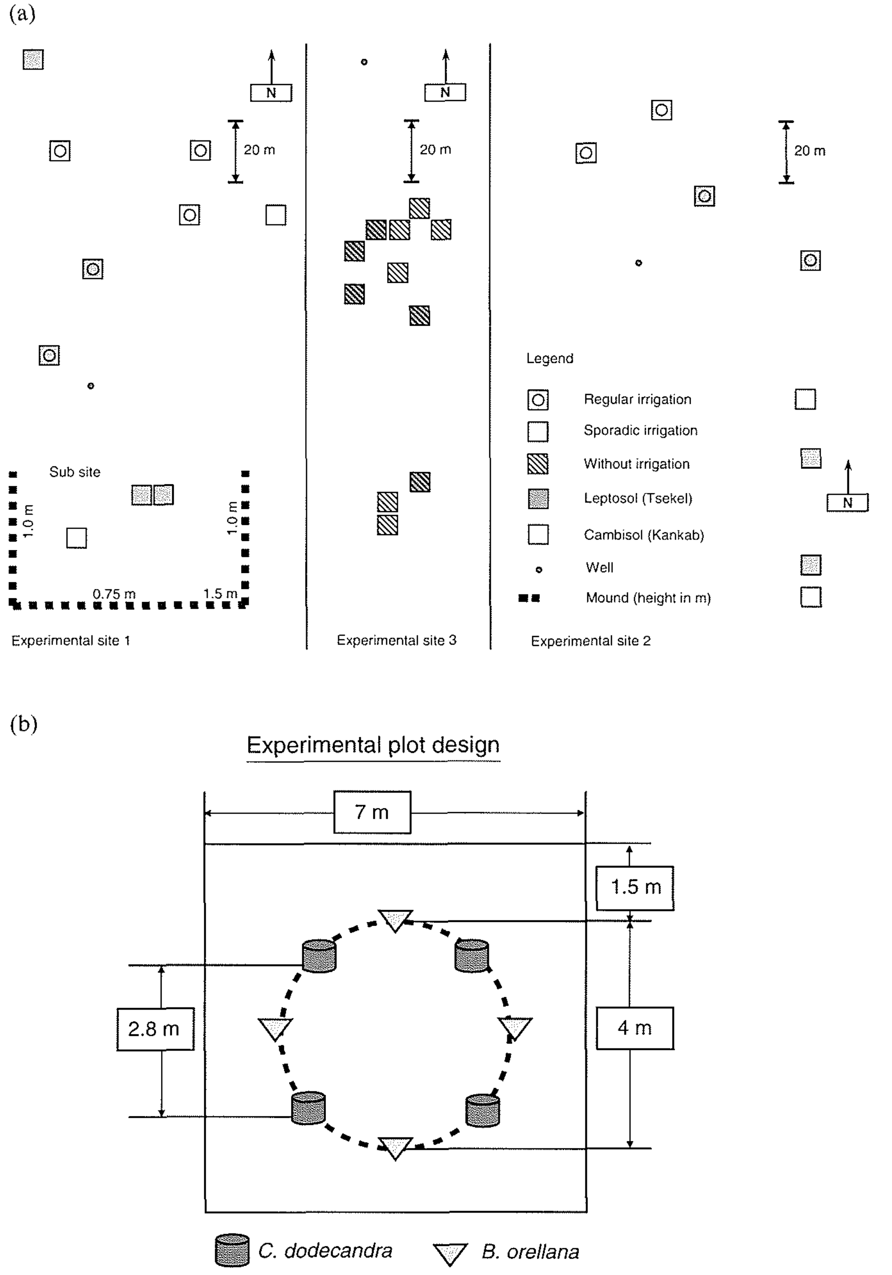

Figure 12.1 (a) Distribution of research plots with three irrigation levels and two soil classes on three experimental sites at X'matkuil, Mérida, Yucatan, Mexico. **(b)** Experimental plot design with Mayan homegarden species *C. dodecandra* and *B. orellana* at X'matkuil, Mérida, Yucatan, Mexico

Experimental Design and Management

We planted 116 *C. dodecandra* and 116 *B. orellana* in 29 circles of 4 m diameter on plots of 7 × 7 m (Figure 12.1a,b). Both species are found in traditional Mayan homegardens, which contribute to the income of the rural households by the production of fruit, seed and/or timber. In our design, the two main factors affecting growth were the two soil types and the three irrigation levels. Seedlings were established in equal numbers on red Cambisol and black Leptosol. Plots on both soils were subjected to three different irrigation levels during the dry season: regular irrigation, sporadic irrigation, and the non-irrigated control. Plots with regular and sporadic irrigation were established on experimental sites 1 and 2 (Figure 12.1a). Plots without irrigation were established on experimental site 3, located between experimental sites 1 and 2. Circles of seedlings were scattered over the experimental sites, choosing locations based on the mosaic of different soil types. Seedlings of the two species were planted alternately in circles. The spacing between *C. dodecandra* individuals was 2.8 m (Figure 12.1b).

Seedlings were obtained from four local nurseries, one private and three federal. Seedlings were sown in the nursery in April 2003, using seeds collected in local communities. They were transplanted to the field between July and November 2003. The height of the planting stock varied between 20 and 40 cm. Before planting, the research site was cleared manually from secondary vegetation, and glyphosate was applied once. The costs for the application of glyphosate on experimental plots were 12 US $. This was an exceptional use of glyphosate for experimental purposes. Planting holes were dug manually to a depth of 40 cm with widths of 30 cm. Seedlings were planted including the soil from nursery bags covering the roots. *C. dodecandra* was planted in July 2002. After hurricane Isidore in September 2002, *C. dodecandra* seedlings were staked to stabilize them. Support stakes were removed in May 2003. In November 2002, lost *C. dodecandra* was replanted to maintain the number of four seedlings per plot. *B. orellana* was planted in November 2002.

Three watering regimes were defined for irrigation during the dry season: Seedlings were either irrigated regularly twice a week from January to June, only at the peak of the dry season (in April and May), or they were not irrigated at all. On plots with regular irrigation, seedlings received 16 L of water twice per week during the entire dry season. Seedlings with sporadic irrigation were irrigated with 8 L of water twice a week for 5 weeks during the peak of the dry season only. Hence, seedlings with regular irrigation received 9.6 times as much irrigation water (in total 768 liters) compared to seedlings with sporadic irrigation that received a total of 80 L of water.

Weeding was carried out manually every 2–3 months during the rainy season, in a circle of about 2 m diameter around individuals. Climbing weeds were removed every 4–8 weeks during the rainy season, and once during the dry season. Survival of seedlings was recorded in September 2002 and in June 2003. Height of seedlings and diameter at 10 cm aboveground were measured in January 2004. Stem length of seedlings was assessed in July 2003 and in January 2004, in order to calculate the stem length increment over the rainy season. Tree height, stem length, and diameter measurements were performed according to Briscoe (1990). Stem length was defined as the actual length of the stem from the top to the ground, including curves and bent parts. Tree height was defined as the shortest distance from the top of the seedlings to the ground level, where the stem of the seedling entered the soil.

Statistical Analysis

Analysis of variance (ANOVA) was performed with individuals, in a full factorial model with the two factors soil and irrigation (SPSS). Significance level was 0.05. Growth parameters from sporadically irrigated plots on the sub-site of experimental site 1 were analyzed separately (see Figure 12.1a).

Results

After 21 months, *C. dodecandra* seedlings attained heights of 200 cm on both soils when irrigated regularly, more than twice their height without irrigation (80 cm on both soils) ($P < 0.001$) (Table 12.1). With only sporadic irrigation, trees grew to a height of 182 cm on both soils, not significantly different from regular irrigation. Seedlings on the sub-site attained heights of 222 cm, without significant differences to sporadic or regular irrigation on the remaining area. The lack of a difference between heights of seedlings on regularly and sporadically irrigated plots was remarkable, as regularly irrigated seedlings received 9.6 times more irrigation water during rainy season than sporadically irrigated ones.

Stem length increments over the rainy season on both soils were significantly different between the non-irrigated control and the two irrigated treatments ($P < 0.001$) (Table 12.2). There was no significant difference between regularly and sporadically irrigated seedlings with stem length increments over the rainy season of 92 cm and 99 cm, respectively. Seedlings without irrigation showed an increment of 26 cm. There was no significant difference between stem length increments on the two soils.

Table 12.1 Height of 21-month-old *C. dodecandra* seedlings on red and black soil with three irrigation levels on three neighboring sites and on the separately analyzed sub-site at X'matkuil, Mérida, Yucatan, Mexico ($P < 0.001$)

Irrigation Level	Soil class Leptosol (L) Cambisol (C)	Height of 21-month-old *C. dodecandra* seedlings (cm)	SE (cm)	N	Sig.
None	L, C	80.2	7.4	34	a
Sporadic	L, C	182.0	9.6	20	b
Regular	L, C	199.4	8.1	32	b
Sporadic, on sub-site	L, C	221.5	14.2	11	b

Table 12.2 Stem length increment over the rainy season of *C. dodecandra* seedlings from 15 to 21 months of age on red Cambisol and black Leptosol with three irrigation levels on three neighboring sites and on the separately analyzed sub-site at X'matkuil, Mérida, Yucatan, Mexico ($P < 0.017$)

Irrigation Level	Soil class Leptosol (L) Cambisol (C)	Stem length increment of *C. dodecandra* from 15–21 months of age (cm)	SE (cm)	N	Sig.
None	L, C	25.6	4.8	34	a
Sporadic	L, C	99.0	6.3	20	b
Regular	L, C	91.6	5.4	32	b
Sporadic, on sub-site	L, C	129.0	9.5	11	c

Table 12.3 Diameter at 10 cm aboveground of 21-month-old *C. dodecandra* on red Cambisol and black Leptosol with three irrigation levels on three neighboring sites and on the separately analyzed sub-site at X'matkuil, Mérida, Yucatan, Mexico ($P < 0.045$)

Irrigation Level	Soil class Leptosol (L) Cambisol (C)	Diameter of 21-month-old *C. dodecandra* at 10 cm aboveground (mm)	SE (mm)	N	Sig.
None	L, C	16.4	1.5	34	a
Sporadic	L, C	34.7	1.9	20	b
Regular	L, C	39.6	1.5	31	c
Sporadic, on sub-site	L, C	43.7	2.6	11	c

On sub-site plots, the increment in stem length over the rainy season was 129, significantly higher than on any plots of the remaining experimental area.

Growth results for the diameter of *C. dodecandra* at different irrigation levels emphasized the comparably high effect of sporadic irrigation on seedling growth. With sporadic irrigation at the peak of dry season, diameters at 10 cm aboveground of 21-month-old seedlings on both soils were 34.7 mm, 100% higher than the non-irrigated control (16.4 mm) ($P < 0.001$) (Table 12.3). With regular irrigation, *C. dodecandra* attained diameters at 10 cm aboveground that were 140% higher than diameters of control seedlings (39.6 mm) on both soils, even though regular irrigation meant 860% more additional water during the dry season than sporadic irrigation. Diameters of seedlings on sporadically irrigated plots on the sub-site were 43.7 mm, as high as diameters of seedlings on regularly irrigated plots.

Irrigation explained most of the growth differences between *C. dodecandra* seedlings ($P < 0.001$). Water availability up to the level of sporadic irrigation is the major influencing factor on growth of *C. dodecandra* during early establishment.

On experimental plots, the height of 21-month-old *B. orellana* seedlings under regular irrigation was 77 cm (SE = 5 cm; N = 30) on both soils. The diameter of stems at 10 cm aboveground of regularly irrigated *B. orellana* was 15.4 mm (SE = 2.0 mm; N = 30). Due to low survival rates of *B. orellana* on sporadically irrigated and control plots, data on height and diameter of *B. orellana* was available for regularly irrigated seedlings only. *B. orellana* seedlings on experimental plots showed a high dependence on additional water supply for survival: their survival rate was 83% under regular irrigation after the first dry season. Survival of this species under sporadic irrigation was 28%.

In September 2002, two months after planting, survival of *C. dodecandra* seedlings was 73%. Of these seedlings, 95% survived hurricane Isidore in September 2002. Fixing the bent seedlings to poles during the following dry season was enough to stabilize them afterwards. In contrast to data on *B. orellana*, our results on *C. dodecandra* show that no water additions were needed for its survival during the dry season. In June 2003, after the first dry season, seedlings of *C. dodecandra* showed high survival rates whether they had been irrigated or not. Regardless of irrigation regime including none at all, survival was between 81% and 88%.

No major incidence of pests and diseases with an impact on apical meristem growth was recorded. During the wet season, larvae and adults of *Coleoptera* were found on *C. dodecandra* seedlings on a number of research plots, but only for a period of a few weeks. At the beginning of the second dry season, leaf-mining insects were observed on part of the tree population. These were most apparent on irrigated trees.

The removal of vines every 4–8 weeks during the rainy season was essential to guarantee undisturbed growth of stems and branches of seedlings. During the dry season, removal of vines was only necessary once.

Discussion

Fast Growth of C. Dodecandra Seedlings

C. dodecandra seedlings grow fast on both soils, and are therefore suitable for agroforestry schemes in the region. The results are in accordance with evidence from the southern peninsula from the State of Quintana Roo, where seedlings of this multipurpose tree species established and grew well on a variety of soils (H. Flachsenberg, 2002, personal e-mail communication, from Tegucigalpa, Honduras). Fast growth of *C. dodecandra* during the first years also agrees with results from small-scale enrichment plantings in cleared forest stripes in southern Quintana Roo (K. Wightman, 2002, personal e-mail communication, from Managua, Nicaragua).

This is the first time that substantial data on growth and establishment of seedlings of *C. dodecandra* on different soils of the northern peninsula was assessed. Literature on growth and establishment of the indigenous tree species in the 'henequen area' is scarce. Apart from observations of Benjamin et al. (2001) in Mayan homegardens on established trees, no documented information on adaptability to different soil types and on water requirements in relation to growth of the species was available.

The Key Role of Water for Growth of Seedlings on Stony, Calcareous Soils

The results indicate that water availability is the dominant factor influencing growth of *C. dodecandra* seedlings in the former 'henequen area'. Benjamin et al. (2001) confirmed the importance of water for growth of multi-purpose tree species. In Mayan homegardens of northern Yucatan, they found hourly sap flow rates doubled in irrigated *C. dodecandra* and *Manilkara zapota* (L.) van Royen. in comparison to the non-irrigated control treatment. For the establishment of seedlings of the fodder tree species *Brosimum alicastrum* Sw., photosynthetic rates in irrigated plants were three to four times greater than in non-irrigated plants (Gillespie et al. 2004).

Our data on the comparably higher impact of sporadic irrigation during the dry season on growth indicate that the adequate timing of irrigation has a major influence on its efficiency. Although the irrigation water input during the dry season was 9.6 times higher for regular irrigation than for sporadic irrigation, height growth of *C. dodecandra* was similar for the two treatments. Diameters at 10 cm aboveground of sporadically irrigated 21-month-old seedlings were comparably high, too. Our results show that with an input of only 8 L per seedling over a period of 5 weeks during the peak of the dry season from April to May 2003, high growth results may be obtained.

The remarkably high height and diameter growth response to only sporadic irrigation on Cambisol sub-site plots on site 1 might be explained by differences in the micro-relief surrounding some of the scattered research plot areas. Terrain elevations of up to 1.5 m, covered by secondary vegetation, at a distance of 20–30 m from plot areas may optimize water supply during dry season. This may lead to observed maximum growth of *C. dodecandra* individuals even on plots with sporadic irrigation only, in comparison to growth on Cambisol plots with regular irrigation that were not bordered by terrain elevations. Additionally, the more recent slashing and burning of fallow vegetation on this part of the experimental area may have had an impact.

Our data showed no significant growth differences between seedlings on black Leptosol and red Cambisol. Even though black Leptosol was reported to possess a higher organic matter content and higher fertility than red Cambisol (Weisbach et al. 2002), this was not reflected in growth of *C. dodecandra* and *B. orellana* seedlings during establishment.

To explain the high growth response of seedlings to irrigation on the stony, shallow soils of Yucatan, the role of rock fragments, estimated at up to 80% of total volume, as a potential additional water reservoir has to be taken into account. To understand the water regime in calcareous soils, the volume and hydraulic properties of rock fragments should be considered because of their influence on water retention and percolation (Poesen and Lavee 1994; Cousin et al. 2003).

Survival of Seedlings under Harsh Environmental Conditions

C. dodecandra is able to establish and survive under harsh environmental conditions. Seedlings are adapted to stony soils, low groundwater table, pronounced drought, and hurricane incidents. Low survival of *B. orellana* seedlings under sporadic irrigation was mainly attributed to planting at the end of rainy season after hurricane damage to the first planting, in November 2002. To guarantee seedling survival after transplanting, planting should be carried out at the beginning or mid of rainy season. Alternatively, seedlings might be irrigated continuously during the first dry season. Nevertheless, regular water supply during the first dry season may have more importance for the survival of *B. orellana* than for *C. dodecandra*.

Additional Influences on Seedling Growth

Temperature and moisture conditions have a strong influence on the development of insects that are associated with *C. dodecandra* (Tamayo Rivera, 2004). Therefore, insect occurrence was restricted to periods of several weeks per year, depending on the insect species. In southern Yucatan, on a private *C. dodecandra* plantation for fruit production, the author observed in the rainy season 2003 a strong incidence of *Coleoptera*. In contrast to this, several smaller *C. dodecandra* regeneration plantings, where seedlings were planted in between fallow vegetation, did not show any comparable presence or damage by phytophagous insects. Hence, as one measure to reduce the negative impact of insects on *C. dodecandra*, it may be recommendable to plant patches of trees, bordered by other vegetation. Further investigations on suitable trap crops should be carried out in order to mitigate damage by phytophagous insects on *C. dodecandra*.

In the research plots, climbing vines invaded seedling stems and branches and inhibited their development. Horvitz and Koop (2001) stated that in a tropical hardwood forest, the removal of vines might improve recruitment of seedlings and saplings of native trees. This may well hold true for tree seedling planting schemes on areas cleared from secondary vegetation.

Shading might have an additional positive influence on seedling survival and growth (McLaren and McDonald 2003). Facilitation of tree seedling establishment by taller vegetation is a recommended management strategy for the restoration of forests on degraded tropical lands (Duncan and Chapman 2003). This is supported by observations on a limited area of experimental plots where seedlings lost their leaves after the removal of adjacent secondary vegetation. This effect might be a consequence of subsequent changes in wind and light intensity, or of a change in the amount of available water due to vegetation removal. Other investigations may show whether shade increases survival and growth of *C. dodecandra*.

Conclusions

C. dodecandra appears a very promising multi-purpose tree for agroforestry systems in northern Yucatan. Apart from its economic potential for providing short-term income by fruit production and long-term income by its valuable timber, the tree species possesses a number of characteristics beneficial to small-scale farmers.

1. *C. dodecandra* grows well on different soils. It established and grew well on stony black Leptosol as well as on red Cambisol. To assess the role of rock fragments for tree seedling growth in the calcareous soils of the peninsula, more research will be necessary.

2. For the establishment of *C. dodecandra* as a tree component, management requirements in terms of labor input are very low. Even with minimal care, seedling growth is good. With only sporadic irrigation during the dry season, remarkable growth of seedlings was achieved.
3. Our data indicate that survival of seedlings of *C. dodecandra* is high even without irrigation during the first dry season after planting.

The next step is to distribute the results of this study to Mayan farmers in northern Yucatan, in order to generate incentives to invest into planting of indigenous tree species on 'henequen lands'. To guarantee successful implementation of results, technical assistance for planting and commercialization of timber and non-timber forest products will be crucial.

In general, this study demonstrates the potential success of research on lesser-known indigenous tree species. An obvious advantage is that they are highly adapted to climatic and soil conditions of their region. If this is accompanied by favorable survival and growth patterns, they may be very suitable for planting. Hence, the evaluation of establishment and growth of lesser-known native tree species with potential for commercialization is an option for the development of promising agroforestry schemes.

Acknowledgments Financial support by the Robert-Bosch-Foundation and the Inter-American Institute for Climate Change Research (IAI) made this research possible. We would like to thank the staff at the Center for Development Research (ZEF) at the University of Bonn, Germany, the Institute for Agronomy in the Tropics (IAT) at the University of Göttingen, Germany, and the Department for Management and Conservation of Tropical Natural Resources (Protrópico) at the Autonomous University of Yucatan, Mexico, for excellent cooperation and organizational support.

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Chapter 13

Tree Foliage Polyphenols and Nitrogen Use in Crop–Livestock Systems of Southern Africa: Strategies for Increasing Efficiency

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Introduction

In southern Africa and Sahelian West Africa, livestock and cropping systems are inextricably linked together. Livestock manure is perhaps the most important soil amendment for crop production. Crop residues provide feed resources during the 7-month dry period. Livestock also provide a source of nutrients, draft power, transport, and is a source of capital for crop production inputs. The potential to increase crop and livestock production in mixed crop–livestock farming systems in these regions is limited by low and erratic rainfall, poor soil fertility, and very limited use of external nutrient sources in the form of inorganic fertilizers and feed supplements. Organic materials consisting of crop residues and vegetation from fallow land and rangeland are the most important sources of nutrients for agricultural production in these farming systems. In managed tropical agroforestry systems large amounts of fresh biomass are harvested and fed to animals or applied to soil. The cycling of plant biomass through livestock faeces and urine, which will be referred to as manure, enhances both livestock and crop production (Powell et al. 1999). For these low input systems to remain viable, plant biomass must be either fed to livestock and manure applied to soils or plant biomass applied directly to soil as amendments.

The rate of decomposition and N release from leguminous plant residues vary enormously, largely due to differences in chemical quality of species and plant parts (Mafongoya et al. 1998). Chemical components which are important in determining the decomposition of legume biomass in the soil are similar to those which dictate their digestibility by animals and their use as animal feeds, namely N, lignin, and polyphenol content.

In both crop and livestock production systems N is the most limiting element to productivity enhancement. Although leguminous tree biomass can provide a cheap source of N, their utilization is limited by the presence of reactive polyphenols. A lot

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

of work has been done on reducing the negative effects on N utilization by crops and animals.

The main objectives of this review are:

- To determine occurrence of polyphenols in legumes widely used in the region and to what extent they limit N-use efficiency
- Compare N process in rumen and in the soil and the potential of models from each system to select materials which are suitable to use as soil organic amendment as well as for fodder
- Assess which management practices can be used to increase N-use efficiency in polyphenol-rich organic materials and finally identity areas future research which will enable the use of polyphenol-rich organic inputs as cheap sources of N for both crop- and livestock-production systems.

The Differences Between Rumen And Soil Ecosystems

The rumen ecosystem differs from the soil ecosystems in a number of important respects (Chesson 1997). Although there are marked differences between these two ecosystems, some parallels can be drawn between the degradation of legume fodder in the rumen and in the soil (Table 13.1). Both processes are microbial, involve a common substrate protein and requiring enzymes with some specificity to achieve breakdown. In both systems, break down by animals is needed before microbial degradation. The factors which limit rate and extent of degradation arise from nature of plant materials, size, and composition of microbial population and activities of soil fauna or host animal (Chesson 1997). Hence, it is possible to compare processes in these ecosystems and develop models to integrate the efficiency of both systems.

Table 13.1 Differences between rumen and soil ecosystems

Rumen	Soil
Constant environment is maintained	The environment is variable in terms of water, temperature, pH
No limiting factors such as supply of nitrogen and phosphorous	N, P, clay mineralogy may affect rate of mineralization
The environment is anaerobic	The environment is aerobic
High number of viable microbes	Variable population of microbes and soil fauna
The animal may select plant material to ingest	Limited choice in selection, although can be manipulated through type of organic inputs applied
Time scale of degradation is 96 h to the maximum	Time of mineralization can be days, weeks, and years
Rate of degradation is 40%–60% within 96 h	This rate can be achieved in year or season
No microbial succession	There may be succession of microbial population in the degradation process

Chemistry and Occurrence of Polyphenols

Polyphenols are the most widely distributed class of plant secondary metabolites with main roles in plant biology, defence against herbivore and human nutrition. Phenolic compounds are defined chemically by the presence of at least one aromatic ring bearing one or more phenol groups. Phenolic compounds can be divided into two groups (1) low molecular weight compounds and (2) oligomers and polymers of relatively high molecular weight. Low molecular weight phenolics occur universally in higher plants and others are species specific. Higher molecular weight proanthocyanadins (also called condensed tannins) are the most abundant polyphenols in woody plants. Hydrolysable tannins have a more restricted occurrence than proanthocyanadins, being found in only 15 of the 40 orders of dicotyledons. Due to large variety of analytical methods and problems with choosing the appropriate standards, polyphenols concentrations reported in the literature vary immensely and might not be comparable with each other (Häthenschwider and Vitousek 2000). A wide variation in polyphenol content of plant parts are due to various factors regulating their synthesis at various levels; ranging from intrinsic species- and genotype-specific factors to various extrinsic environmental factors, which interact with each other and this results in a wide range variation of plant polyphenols among and within species through time and space. In this review polyphenols will be used to refer to Pas or tannins.

Role of Polyphenols in Nitrogen Cycling in the Soil–Plant–Animal Continuum

Several papers were published in the 1960s showing that polyphenols could inhibit the activity of digestive enzymes or precipitate nutritional proteins (Handley 1961). Much of the research have been devoted to polyphenols as anti-herbivore compounds neglecting their role in other ecosystem processes. Polyphenols have been known to be regulators of soil processes where it has been shown that they inhibit nitrification, as well as decomposition nutrient cycle. Nutrient mineralization by soil organisms is generally regarded as a rate-limiting step in the nutrient cycle, and factors involved in the control of the process include climate, substrate quality, and decomposer organisms (Heal et al. 1997). Polyphenols are known to affect litter quality, at times having a larger effect on decomposition rates than more frequently measured parameters such as N and lignin.

In addition to affecting organisms responsible for decomposition and specific N transformations, polyphenols can alter N availability by complexing with proteins. Polyphenol–protein complexes originate either during senescence of plant tissues when polyphenols stored in the vacuole come into contact with cytoplasmic proteins, or in the soil when they complex with protein from litter or with extracellular envzymes from microbes. Polyphenol–protein complexes are resistant to most decomposing organisms. The rate of N mineralization decreases substantially with increasing protein complexing or binding capacity of polyphenols (Northup et al. 1995; Mafongoya et al. 1998). High levels of polyphenols might inhibit N mineralization but also correlate positively with release of dissolved organic nitrogen (Northup et al. 1995).

Phenolic compounds can directly affect the composition and activity of decomposer communities thus influencing rates of decomposition and nutrient cycling. Different soluble polyphenols are known to inhibit or stimulate germination of spores and hyphal growth of saprotrophic fungi. Polyphenols have been suggested to inhibit nitrifiers (Rice and Pancholy 1973) and, depending on the type of polyphenols, may suppress or stimulate activity of symbiotic N-fixing bacteria. Soil macrofauna can enhance N_2 mineralization from SOM by several mechanisms. High concentrations of polyphenols might restrict the activity and abundance of such fauna (Neuhauser and Hartenstien 1978). There are no studies from tropical agro-ecosystems which have looked at these microbial processes and polyphenol interactions.

The buccal cavity is the first site at which proteins and polyphenols have the opportunity to interact, and it represents an additional dimension to the rumen-soil comparisons. Saliva of some ruminants, including goats, have been shown to contain proline-rich proteins that complex with tannins, minimizing the effects of the tannins on protein digestion and absorption in the rest of the gastro-intestinal tract (Robbins et al. 1991). The tannin–protein interactions in the buccal cavity have a direct effect on intake (Chesson, 1997).

Feeding most of the tanniniferous browses to ruminant livestock at levels below 25% of diet increased intake of the poor quality roughages (Dzowela et al. 1997; Nherera et al. 1998; Hove et al. 2001). However, inclusion of tree leaves at levels above 25% resulted in substitution of the leaves for the poor quality roughages. The increase in N supply on feeding protein-rich tree foliage partly explained the increased intake of the N-deficient basal diets used in the studies.

Tree foliage is primarily a source of protein for both the rumen microbes and the host animal, hence the importance of understanding the interactions between proteins and tannins along the gastro-intestinal tract. The interactions occur at several sites (buccal cavity, rumen, abomasums, small and large intestines) along the gastro-intestinal tract. The interactions that occur in the rumen are the most important since it is in this organ that most of the plant material occurs. Tannins were shown to depress digestibility of proteins by inhibiting microbial enzymes (Hove 1999) and/or forming indigestible complexes with proteins and cell wall carbohydrates (Perez-Maldonaldo 1997; Hove 1999). However, shrub legume species was an important factor in determining the digestibility of N. While *L. leucocephala* had levels of proanthocyanidins that were comparable to *C. calothyrsus*, and much higher than *A. angustissima*, the rate and extent of N degradation in the rumen did not correspond to proanthocyanidins content (Figure 13.1). These responses were similar to those observed for N use by crops where *L. leucocephala*, proanthocyanidins were observed to have low reactivity. The proanthocyanidins in *L. leucocephala* may be less reactive because they are of small size as they showed highest relative degree of polymerization on drying (Hove et al. 2003).

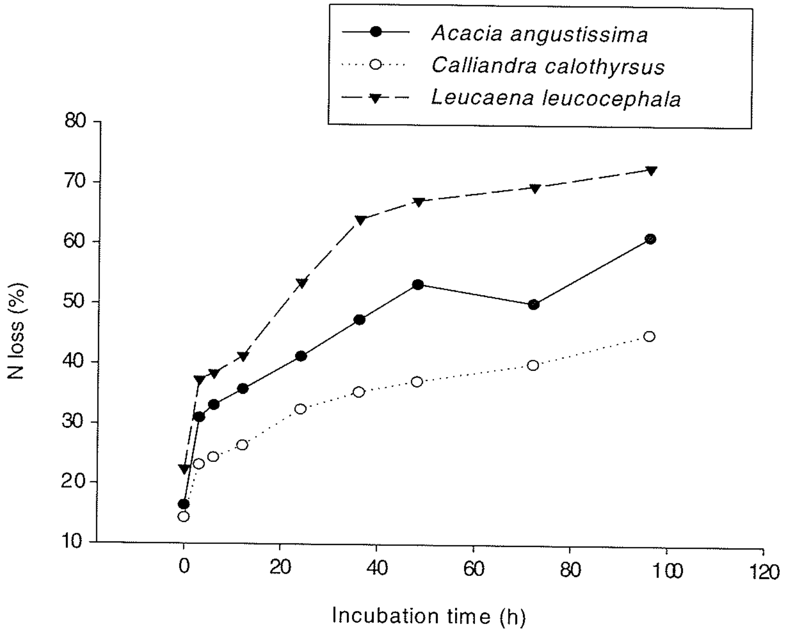

Figure 13.1 Rumen degradation patterns for N in dried leaves of multipurpose shrubs grown in Zimbabwe

While the amount of N retained by the animal is a good indicator of the utility of the leaves as protein supplements, it does not adequately measure use efficiency. The synchronous supply of adequate N for both the rumen microbes and the host animal, together with N retention, is an indicator of N-use efficiency. The feeding of leaves of high rate of N degradation in the rumen, such *as G. sepium, S. sesban*, and *Securinega virosa*, results in asynchronous release of N and energy in the rumen, leading to loss of N in urine. On the other hand, feeding leaves of very low tannin-induced rate and extent of degradability in the rumen such as *C. calothyrsus* result in sub-optimum rumen conditions. It may be proposed that while the rate of release of *C. calothyrsus* N may match the release of energy from poor quality roughages, the benefits are in most cases outweighed by the negative effects of tannins on N degradation. The net result is a N-starved rumen ecosystem that leads to negative or low N retention by the animal. The result is similar to that observed when species whose rumen N degradation patterns are largely influenced by lignin, e.g. *F. macrophylla* are fed.

Feeding tanniniferous browse was shown to shift N excretion towards faeces (Table 13.2 and Figure 13.3). This may be explained by the fact that the proanthocyanidins in leaves reduce degradation of N in the rumen by forming complexes. The stability of these complexes depends on the species as shown in Table 13.2 and so does the shift of N excretion between faces and urine. Some species, e.g. *A. angustissima*, form complexes that are unstable in the post-rumen

Table 13.2 Rumen and post-rumen loss of N (g/kg) in the leaves of fodder shrubs grown in Zimbabwe as measured using the mobile nylon bag technique using steers. (From Ndlovu et al., 2002.)

Browse	Level of leaf in diet (g/d)	Nitrogen intake (g/d)	Faecal nitrogen (g/d)	Urine nitrogen (g/d)	Retained nitrogen (g/d)	References
Acacia angustisima	0	2.6	3.27	0.242	−0.97	Hove (1999)
	80	4.9	3.45	0.213	1.27	"
	160	6.4	4.13	0.408	1.86	"
	320	10.3	5.49	0.927	3.92	"
Calliandra calothyrsus	80	3.9	4.29	0.136	0.54	"
	160	4.5	3.79	0.130	0.54	"
	320	6.5	5.83	0.115	0.56	"
Leucaena leucocephala	80	4.5	3.18	0.412	0.92	"
	160	7.2	5.10	0.608	1.47	"
	320	11.7	5.03	0.850	5.80	"
A. angustissima	231	9.2	3.8	2.1	3.3	Dube (1993)
A. karroo	189	5.6	4.6	0.5	0.5	"
A. nilotica	127	4.1	2.0	0.9	1.2	"
Colophospermum mopane	136	1.9	1.8	3.0	−2.9	"
Gliricidia sepium	225	7.9	3.2	1.7	3.0	"
L. esculenta	128	6.5	3.5	0.16	2.94	Nherera et al. (1998)
L. diversifolia	123	6.0	2.6	0.34	3.06	"
L. pallida	123	5.9	2.6	0.32	2.98	"
C. calothyrsus	126	5.7	2.5	0.27	2.93	"

environment resulting in the N being digested and relatively less excreted in faeces. This characteristic of *A. angustissima* tannins may make this species an important source of digestible rumen undegraded N that is usually required by highly producing (milk or meat) animals. On the other hand complexes formed between highly reactivity tannins such as those of *C. calothyrsus* tend to be more stable and little digested post-rumen (Table 13.3). Proportionally less N is excreted in urine when tanniniferous browse are fed compared to those of low tannins and commercial supplements such as cottonseed meal (Table 13.3).

In the smallholder farming systems of southern Africa where livestock manure is an important source of nutrients for crop production, the shift of N excretion through faeces would be desirable if the N is eventually available to the crops. Urine N is largely lost as ammonia through volatilization and not used by crops. It has been observed that most of the faecal N is bound to cell wall carbohydrates and may not be readily available for uptake by crops (Mafongoya et al. 2000).

The sum effects of polyphenolics on intake and digestion are reflected in production measures such as growth and milk yield. Species that were observed to have proanthocyanidins of high reactivity also resulted in comparatively lower milk yield. However, more studies are required to quantify the effects of feeding tree foliage on animal production (Table 13.4).

Table 13.3 Intake of PA (g/d) and faecal excretion of NDIN and ADIN by goats fed graded levels of cottonseed meal (CM) or leaves from shrub legumes *A. angustissima* (AA), *C. calothyrsus* (CC), and *L. leucocephala* (LL) as supplements to native pasture hay (NPH)

Species	Rumen	Postrumen	Total tract
A. angustissima	301	156	457
C. calothrysus	277	35	312
L. leucocephala	440	149	589
Standard error of difference	36.8*	20.2***	13.0***

Level of significance; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Table 13.4 Tree foliage N intake and utilisation in Zimbabwe

Species	Provenances	Dry matter digestibility (g/kg)	Polyphenol content	Protein-binding capacity	Maize yield (t/ha)	Milk yield (kg/d)
L. collinsii	45/85	492	12.1	Medium	2.0	
L. collinsii	51/88	643*	–	Low	–	
L. diversifolia	53/88	491	6.7	High	1.4	
L. diversifolia	35/88	–	6.2	High	1.5	
L. esculenta	47/87	633	–	Medium	–	
L. esculenta	52/87	523	5.0	Medium	1.8	
C. calothyrsus	Ex-Embu	485	11.3	High	1.5	
C. calothyrsus	Suchitepequez	358				8.1
A. angustissima	37/88	481	7.2	Medium	2.4	11.6
L. leucocephala	Hawaii	669				14.4
G. sepium	14/84	791	2.2	Low	2.9	
L. esculenta	Ex.Machakos	–	7.6	High	1.1	
L. pallida	–	–	5.2	High	1.3	
F. macrophylla	–	421	10.5	High	1.0	
S. sesban	Kakamega	910	11.2	Low	3.4	
C. cajan	–	796	4.2	Low	2.7	12.3

Managing Polyphenols for Efficient N Use

Efficiency of nutrient use depends on both the efficiency of acquisition of nutrients (nutrient capture) and the efficiency with which nutrients are then utilized by a growing plant or animal (conversion efficiency). Litter decomposition can thus be manipulated to improve nutrient-use efficiency with two strategies: (1) to regulate the rates of release of nutrients to improve the synchrony of nutrient supply with crop and animal demand, and (2) to provide a more favorable environment for plant growth. Improvements in the environment for plant growth may result in more extensive root development and thus enhance nutrient capture, or may improve the efficiency of nutrient use by enhancing plant growth in general. These two goals relate to the short-term improvement of nutrient availability and the longer-term improvement of soil organic matter. The long-term effects of building up some SOM pools may be more important than short-term nutrient release patterns. It is commonly found that significant results are obtained after several years of green manuring. The soil ecosystem takes years to show effects of organic inputs. The effect of organic inputs on both of these strategies is highly dependent on the quality of those inputs. Nutrient availability can be affected both directly by the contribution of nutrients released during decomposition, or indirectly through the effects of decomposition by-products, such as organic ions reducing the P-fixation capacity of the soil (Hue 1991). The soil organic matter content and the relative proportion of different organic matter fractions, which have different roles in nutrient cycling and determining soil structure, also depend on the amount and quality of organic matter inputs. Thus the potential exists for manipulating soil fertility in various ways depending on the specific requirements of the soil and cropping system being managed.

Some of the species that lead to inefficient use of N when fed to ruminants are agronomically adapted to the sandy infertile soils, high fluctuations in temperatures, and to droughts. It is important that their agronomic advantage is exploited to the benefit of the resource-poor smallholder farmers in the region who have limited access to the commercially available alternatives. The goal of managing is to maximize crop or livestock products at minimum N input. Many studies were undertaken to develop management strategies that exploit the chemical composition differences among the leaves of the various species, and between the leaves and the commercially available sources of nutrients for crops and livestock. These included species selection, state of leaves at use, mixing prunings of different quality, time of pruning application and feeding on N-use efficiency, brown manure versus green manure. The results of these management practices will be discussed in detail in the following sections.

Species Selection

Species selection is the most obvious method of selecting organic resources of particular quality although other consideration will often dictate the choice of agroforestry trees. There are several hundred species of leguminous trees with potential for fodder and soil fertility improvement. Most have not been investigated and a few are in current use (Table 13.4). Of the 5000 known nitrogen-fixing woody species, Brewbaker (1986) suggested that only about 80 leguminous trees have been used for fodder and soil fertility improvement in tropical farming systems. A list of those widely used in southern Africa is shown in Table 13.4. There may be additional species with a potential and within each species there is genetic variation which can be exploited. Other species may have potential but are not in significant use.

Many of the agronomically superior taxa such *L. diversifolia*, *L. pallida*, and *L. triachandra* (Mullen et al. 1998) and *C. calothyrsus*, Table 13.4) have high concentration of polyphenols that are likely to adversely affect forage quality and rates of N release when used as green manures. However, considerable intraspecific variation in polyphenols content within these taxa suggests that there is scope for selection of vigorous accessions with lower tannin content and therefore better forage quality and rates of N mineralization. A number of low tannin taxa, including *L. collinsii*, *L. macrophylla*, *L. multicapilila*, *L. salvadorensis*, *L. shannonni*, and *L. trichodes* have been identified as having forage quality equal to or better than *L. leucocephala* (Dalzell and Shelton 2002).

Unfortunately these accessions, with the exception of *L. collinsii* ssp. *collinsii*, are agronomically inferior to most of the tannin-rich species and accessions (Mullen and Shelton 1998). There is scope to use low tannin accession identified in several studies as parents in interspecific hybridization programs that aim to improve forage quality of agronomically desirable accessions by minimizing tannin concentration. Such efforts have proved useful by the results of Wheeler et al (1994) and offer a huge potential to widen tree forage legume genetic base for use in the tropics.

While the content of the polyphenols is important, the quality of polyphenols, as shown by their protein-binding capacity is more important (Mafongoya et al. 1998, Table 13.4 and Figures 13.2 and 13.3). The chemical nature (protein-binding capacity) of *Leucaena* spp, tannin have been observed to be different (McNeill et al. 1998; Nherera et al. 1998) and of various tree species (Mafongoya et al. 1998) suggesting that both the monomeric composition and structure of tannins will differ within the same genus. (McNeill et al. 1998) also showed that tannins of the same molecular

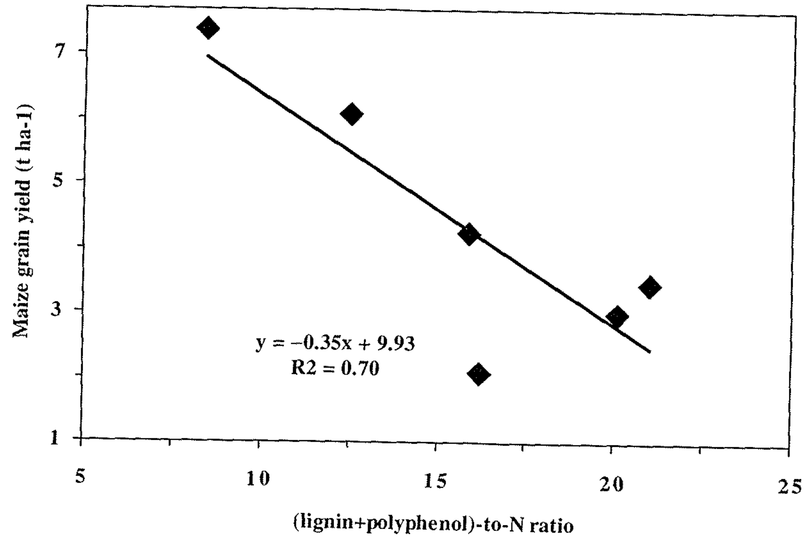

Figure 13.2 Effects of polyphenol and lignin levels on maize yield

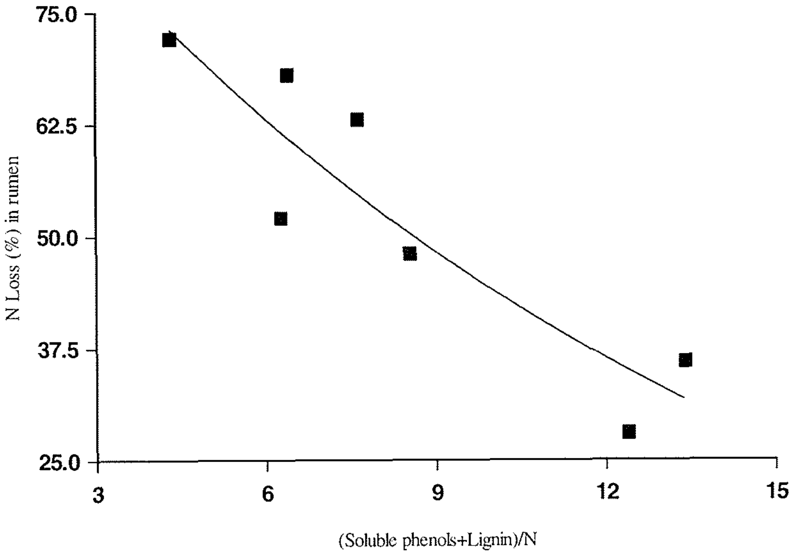

Figure 13.3 Relationship between phenolic compounds and N contents in leaves of seven tropical shrubs and the degradation of N in the rumen

weight from different *Leucaena* spp had different protein-binding capacity, further emphasizing the biochemical differences between tannins of these species. Considerable interspecific and interaspecific variation in tannin content, chemistry structure/molecular weight has been observed in *Sesbania sesban* (Heering et al. 1996). This indicates a huge potential to select species which have low protein-binding capacity, good agronomic performance, and high potential for use as fodder or green manures for N inputs in cropping systems.

Generally, species with high levels of reactive polyphenols release N slowly in the soil and in the rumen, leading to lower maize and rumen microbial yields (Figures 13.2 and 13.3). In contrast, species with low levels of reactive tannins lead to faster N release in the rumen and soil, leading to high crop yields and animal productivity (Table 13.4).

State of Leaves at Use

It is not only the quantity of polyphenols found in the prunings that matter, but also their quality. The quality of polyphenols is determined by their structure and their reactivity, which is their protein-binding capacity. The protein binding of polyphenols in MPT prunings is negatively correlated with N mineralization rates (Handayanto et al. 1994; Mafongoya et al. 1998). Oven drying and heating lowers the extractability of polyphenols in a range of tropical legumes (Mafongoya et al. 1997a,b). Extractable and water-solube polyphenols are more reactive than insoluble polyphenols (Mafongoya et al. 1997a). Sun drying the prunings of MPTs reduces the amount of extractable polyphenols of various MPT species (Mafongoya et al. 1997a). This has implications of the effectiveness of prunings when they are applied fresh or sun dried to crops as sources of N or fed to livestock as fodder. The application of fresh prunings doubled the maize grain yield compared to sun dried prunings (Figure 13.4) using four species such as *Gliricidia sepium, Acacia angustissima, Flemngia macrophylla*, and*Senna siamea*.

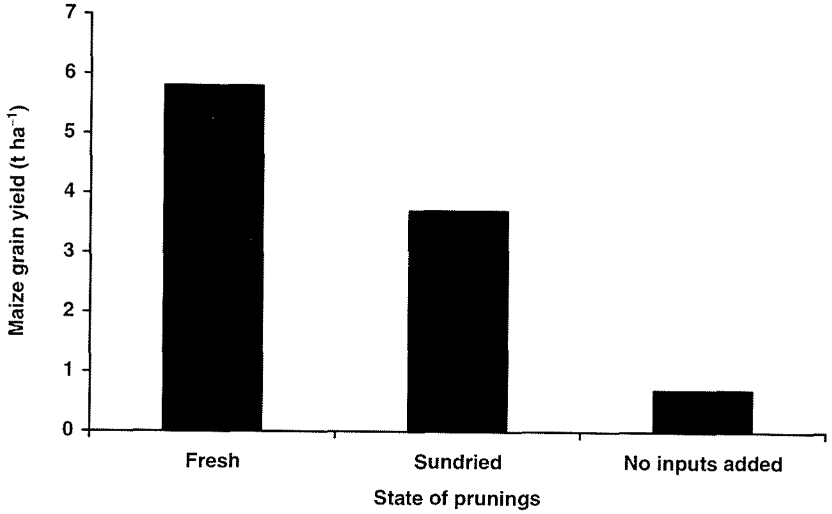

Figure 13.4 Effects of state of prunings on maize yield (t/ha)

The effect of fresh or sun dried prunings on maize grain yield can be explained in terms of their N release patterns. Fresh prunings may contain less polymerized polyphenols, which have few binding sites for proteins and so more N is released. The polyphenols of sun dried prunings undergo oxidative polymerization due to heat which creates bigger polymers of the phenolic acids that may bind N and so less N will be released.

The MPT species also had a significant effect on maize grain yield (Figure 13.5), which was related to their pruning quality. *Gliricidia sepium* and *Acacia angustissima*, which are high-quality prunings, led to significantly higher maize yield compared to *Flemingia macrophylla* and *Senna spectibilis* prunings of low quality.

Cattle and goats readily consumed most of the browses in the dry or fresh state, except for *A. angustissima, G. sepium*, and *C. cajan*, whose intake by goats improved on drying (Hove, unpublished data). While tannins seem to be responsible for the low intake of fresh *A. angustissima*, other compounds are probably responsible for reduced intake of fresh *G. sepium* and *C. cajan*. Tannins in fresh *A. angustissima* may have been more reactive, causing astringency and reducing intake. The tannins complex with biomolecules in the leaves and become less reactive on drying, resulting in improved intake. Depressed intake of fresh *G. sepium* compared to dried leaves is

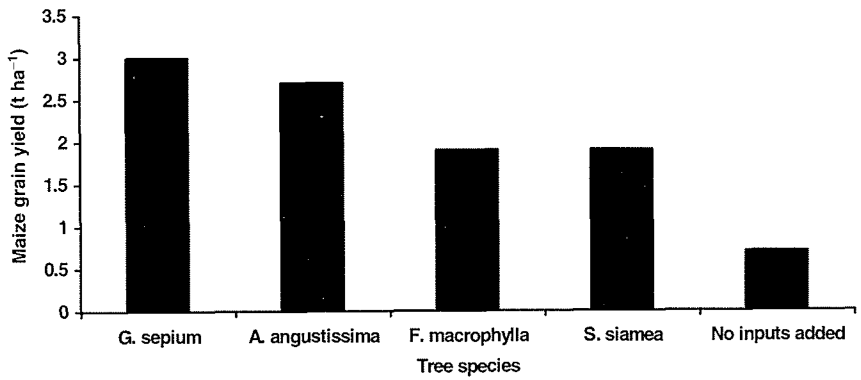

Figure 13.5 Effects of prunings from various tree species on maize yield (t/ha)

well known and is attributed to coumarins that are volatile and off putting to the animals. It is possible that volatile compounds are all also present in *C. cajan* leaves.

The rumen degradation pattern and retention of N did not differ with status (fresh or dry) of browse at feeding even when *in vitro* dry matter and organic matter digestibility and chemical composition differed with status of browse (Hove, 1999; Hove et al. 2003). These results contradict those observed elsewhere (Palmer and Schlink 1992) who observed reduced intake, digestibility, and live-weight gain with drying compared to feeding fresh leaves. Species and the species interactions with the drying compared to feeding fresh leaves. Species and the species interactions with the biophysical environment could probably explain the different results. These results have important practical implications in that farmers are able to choose to feed (fresh or dry) browse that suits their social and economic circumstances and then have a large impact on productivity.

The improved N-use efficiency observed for crops when fresh leaves were used compared to dry was not always observed for livestock although the trend was to reduce the digestibility of leaves on drying. The explanation for the differences is not clear but the presence of water in the rumen resulted in the hydration of the leaves, thus facilitating better attachment of microbes to the forages compared to the soil system. In addition, the complexes formed on drying could have been weak and degraded by the rumen microbes. However, feeding dry rather than fresh leaves of some species such *A. angustissima* was shown to improve acceptability, and as a result, N intake.

Mixing Prunings of Different Quality

Mixing prunings of different qualities is one obvious approach to regulating the rates of decomposition and nutrient (especially N) release from prunings. Mixtures can be comprised of different plant parts of a single species or of mixtures of material from species with widely differing quality. Regardless, the same rules will govern the

decomposition interactions between the different quality materials. Effects of mixing types of plant tissues in prunings were investigated by (Constantinides and Fownes 1994).

In this study it was shown that the complex pattern of N accumulation or release was attributed to the immobilization in the twig fraction, thus proving the hypothesis suggested by (Oglesby and Fownes 1992). The mixed leaf and twig incubations deviated from mineralization expected from leaves and twigs acting independently, thus providing some evidence for the interaction in the mixtures.

The resulting decomposition pattern of a mixture may be directly the mean of the decomposition patterns of the two (or more) litters. There may be no interaction between the two litters but both behave as if decomposing in isolation. Alternatively there may be significant interactions between the litters such that the rates of decomposition and N release are altered and/or the amount of N released is changed in an predictable way (Zingore et al. 2003).

The mixture of *Tithonia diversifolia* and *C.calothyrsus* showed good improvement of synchrony of N. The mixture gave maize yield than *Tithonia diversifolia* alone. The mixture had more mineral N in the top 20 cm of soil compared lower soil depth. The improved synchrony between N release and crop uptake was due the effect of *C.calothyrsus* reducing rapid N release from *T.diversifolia* resulting in delayed N release which improved N availability to the maize and less N leaching (Zingore et al. 2003).

For there to be strong interactions in decomposition between prunings of different types, the constituents of the different prunings must either be available to microorganisms at the same time, or must be able to interact directly. Thus unless the leaf litters are ground and mixed together very finely such interactions can only be due to movement of soluble constituents. The three types of soluble compounds which can move, resulting in interactions between litters are: (1) compounds that contain readily available carbon as a substrate, (2) compounds which contain readily available N, or (3) soluble polyphenols which can complex with proteins and render them resistant to immediate microbial attack. Lignin is degraded only slowly, and can protect other cell wall constituents such as cellulose from microbial attack due to the conformation within the cell wall (Chesson, 1997). Strong interactions between lignin and other recalcitrant substrates are thus unlikely to occur until later stages of decomposition when residues become more intimately mixed, and fungi hyphal networks can bridge between resources (Rayner, 1994).

Experiments mixing residues of *Gliricidia sepium* with *Peltophorum dasyrrachis* at varying proportions revealed a linear trend in total soluble polyphenols. However, the mixtures had a very low protein-binding capacity, similar to pure *Gliricidia* residues, unless more than 50% of the material was derived from *Peltophorum*. When more *Peltophorum* prunings were added the protein-binding capacity rose sharply indicating that large quantities of soluble protein from the *Gliricidia* residues were able to bind to and saturate the reactive polyphenols of *Peltophorum* up to 50% (Handayanto et al. 1994, 1997). Decomposition and N release, and subsequent N recovery by maize, were inversely related to the protein-binding capacities of the mixtures, indicating that PBC is a robust predictor of N mineralization (Handayanto et al.

1997b). Within intact tissues, reactive polyphenols are localized either within the vacuoles or in the cell walls, thus protecting enzymes and other proteins from complexation. Indeed in some species polyphenols are localized into particular cells such as trichomes (Li et al. 1996), which may limit their influence on decomposition rates.

A secondary mechanism by which decomposition interactions between residues can occur is where one residue alters the physical environment of another residue, for instance, when recalcitrant litter create surface mulch which increases moisture availability in the underlying litter and soil. (Tian et al. 1993) found that when there was sufficient moisture, a low quality mulch of *D. barteri* produced lower maize yields, than did a high-quality mulch of *Gliricidia* that released more N. By contrast, during the dry season the lower quality mulch produced higher maize yields because of the improved microclimate for decomposition and mineralization below the mulch. Another explanation for the increased moisture effect is that higher SOM leads to increased water retention.

Mixing of fodder sources of different chemical characteristics was studied extensively and mixtures of species with different types of tannins were studied (Dube, 1993; Mafongoya 1997; Hove, 1999). In addition, mixtures of tree foliage with commercially available feeds and fertilizers were also evaluated. Mixtures of species with relatively high reactive tannins (*C. calothyrsus, A. angustissima*) with those of relatively low reactivity (*L. leucocephala, G. sepium* and *S. virosa*) were evaluated for dry matter intake and growth. In most cases synergistic effects were observed (Table 13.5a). On their own, leaves with highly reactive tannins starve the rumen system of N while the fast degrading leaves result in asynchronous release of N and energy for microbial synthesis in the rumen. Mixing synchronizes the release of N with microbial requirements, leading to a more efficient and productive rumen system, and subsequently better animal performance. Besides improving N digestion, it minimizes losses through urine. The unique characteristic of *A. angustissima* N digestion along the tract (moderate rumen and high post-rumen digestion) may be exploited in mixtures that are fed to high producing animals.

Table 13.5a Dry matter intake and growth rate (g/head/d) of goats fed dried leaves of multipurpose shrubs in Zimbabwe. (From Hove, unpublished data, 1996, Zimbabwe.)

		Supplement						
		AA	3AA	LL	3LL	AL	3AL	SED
Intake								
	Native pasture hay	260a	336d	305b	326d	299b	337d	9.9
	Total dry matter	363a	439cd	434bc	453cd	417b	457e	10.0
Growth rate		6	5	13	21	20	21	8.4

AA – *A. angustissma* daily; 3AA – *A. angustissima* every 3 days; LL – *L. leucocephala* daily; 3LL – L. leucocephala every 3 days; AL – mixture (1:1) of A. angustissima and L. leucocephala daily; 3AL – mixture (1:1) of *A. angustissima* and *L. leucocephala* every 3 days

SED – standard error of differences between means

abcRow means with different letters differ ($P < 0.05$)

Table 13.5b Intakes of hay, browse, and total dry matter (g/d) by goats fed mixtures of *Acacia karroo* (AK), *Acacia nilotica* (AN), and mature hay. (From Dube, 1996)

Browse	Hay	Browse	Total DM
AK	417	292	709
3 AK: 1 AN	417	389	806
1 AK: 1 AN	389	403	792
1 AK: 3 AN	417	375	792
AN	431	236	667
Hay	778	–	778
Standard error	11.4	23.6	31.4

Dube (1996, Table 13.5b) evaluated mixtures of species with different types of tannins. *Acacia karroo*, a species palatable to goats but with high levels of proanthocyanidins that depress digestibility was mixed with *Acacia nilotica*, a species that has poor palatability and contains high levels of hydrolysable tannins and no proanthocyanidins. Feeding the mixtures resulted in higher total and basal diet intake and N retention compared to feeding either alone. These positive effects could be due to the interactions between the proanthocyanidins and the hydrolysable tannins in a manner that we cannot explain at the moment. Besides nutritional benefits, mixing leaves from different species has added benefits to the farming systems as this increases biodiversity at farm level.

Mixing *C. calothyrsus* and *A. angustissima* leaves with soybean meal and cottonseed meal resulted in synergistic effects on intake and N digestion and retention (Hove, 1999; Figure 13.6a). These responses may be explained by the synchronous release of energy and protein on mixing of these sources of N of contrasting degradation rates. Similar responses were observed in soil system and crops (Figure 13.6b).

Mixing of small doses of inorganic nutrient source such N, P, and K also doubled the maize combined with low quality prunings of *Leucaena pallida* and *Leucaena esculenta* applied alone. The mixture of organic inputs of high quality from *Gliricidia sepium* and inorganic inputs has less significant effect (Figure 13.6b). These results indicate that N could not be released in synchrony with crop demand from low-quality inputs, hence, the crop could be N deficient. However, addition of inorganic N helped to improve the synchrony. However other interactions beyond N limitations needed to be studied also.

Time of Pruning Application and Feeding on N-use Efficiency

The time at which the prunings are applied in relation to crop growth stages can potentially increase the N-use efficiency from prunings. Studies by (Mafongoya et al. 1997b) showed that time of prunings application, the amount and the quality of prunings are important factors in improving maize grain yield and N uptake and recovery (Mafongoya et al. 1997d). Applying all prunings at planting gave the

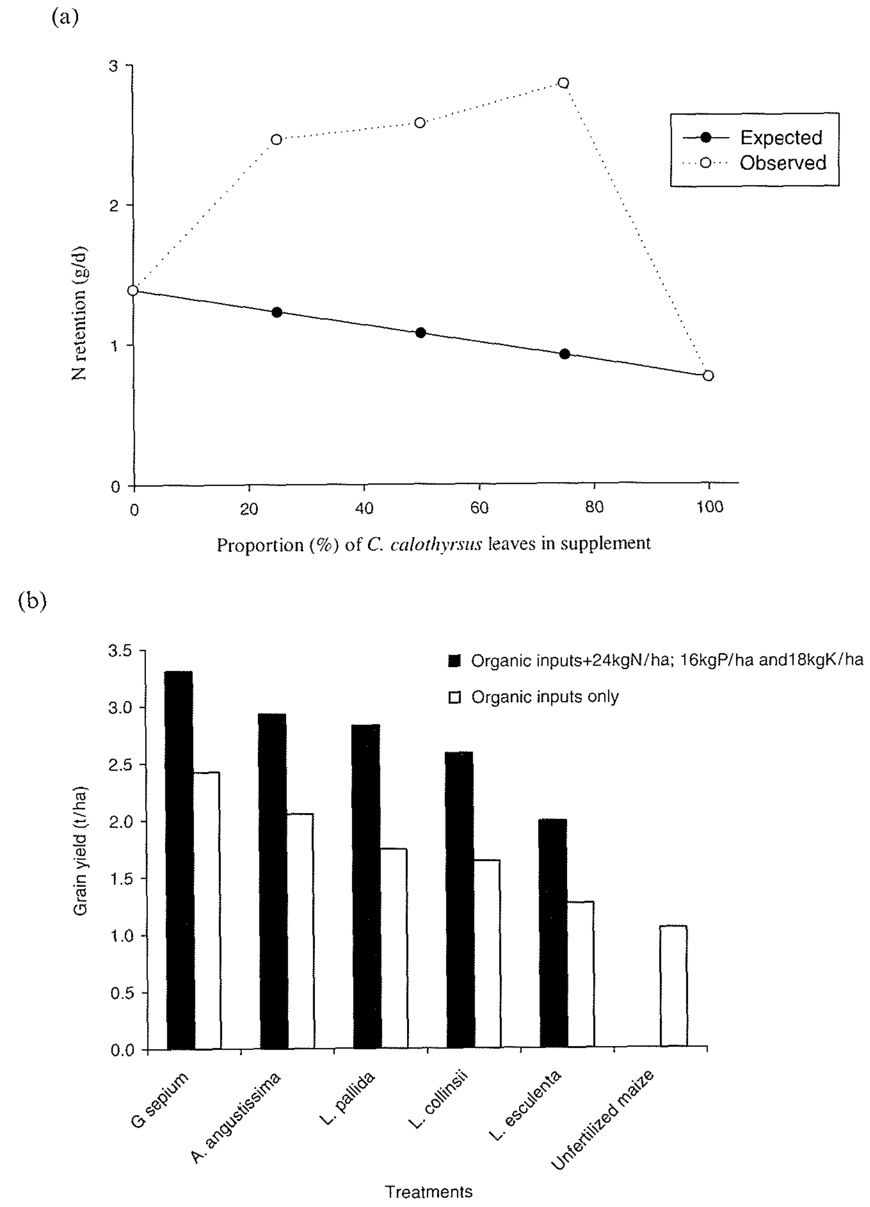

Figure 13.6 (**a**) Effects of feeding mixtures of soybean meal and dried leaves of *C. calothyrsus* as supplements to native pasture hay on N retention by goats (**b**) Effect of mixing organic and inorganic nutrient sources on maize yield

highest maize grain yield, N uptake and recovery with *calliandra*. However, with high quality such as *leucaena*, prunings applied at planting, 2 or 4 weeks after planting maize did not differ in terms of maize grain yield, N uptake and recovery. Split application of prunings was inferior in terms of maize grain yield and N recovery compared to a one time application of all available prunings at the time of planting maize. Higher maize grain yield, N uptake and recovery can be achieved by incorporating high-quality prunings at 2 weeks after maize planting. Application of prunings 2 or 4 weeks after maize planting will result in lower N recovery but may lead to higher residual N effect in the subsequent crop using lower quality prunings (Mafongoya et al. 1997c).

Studies by Hove (1996) evaluated the effects of daily or every third day feeding of *A. angustissima* and *L. leucocephala* leaves, singly or in mixtures, on intake and growth rates of goats Table 13.5a). Compared to daily feeding, every third day feeding of *A. angustissima* increased native pasture hay and total dry matter intake but not growth rate. Feeding *L. leucocephala* increased native pasture hay intake but not total dry matter intake. The 1:1 mixture of leaves from the two species had responses similar to those observed when *A. angustissima* was fed alone. The increase in intake was probably due to an improved rumen environment as a result of synchronized release of nitrogen and energy and availability of a large quantity of readily digestible fibre (Ndlovu et al. 2002). This would increase the population of cellulolytic microbes, leading to increased rate and extent of degradation of cell wall carbohydrates, and consequently intake. An additional advantage of giving the leaf supplement in large amounts is the loading of the rumen with readily digestible cell wall that could serve as a reservoir for cellulolytic microbes. These responses have important implications for practical feeding of livestock in labor-constrained systems like those found in southern Africa.

Brown Manure vs Green Manure

A choice must be made between the allocation of organic resources, whether they should be used for livestock feed or as organic fertilizers for crop production. The following hypotheses in the role of livestock in managing nutrient cycling in crop livestock farming systems were explored:

- Nutrient supply of high-quality materials is reduced by passage through livestock
- Nutrient supply of low-quality materials is improved by passage through livestock
- Manure quality can be manipulated by choice of feed supplements.

Many studies have shown that browse leaves or fodder leaves had a higher rate of decomposition compared to manure for crop production (Ikpe et al. 2003; Mafongoya et al. 2000; Delve et al. 2001). This shows that high-quality organic inputs have potential for direct soil amendment than manure (Figure 13.7, Mafongoya et al. 2000). However, lower-quality materials of fodder species are more beneficial when applied as manure over direct application of the leaves to soil (Delve et al. 2001). However, for phosphorous cycling when browse leaves are applied to soil there is P immobilization compared P mineralization in manures (Powell et al. 1999; Mafongoya et al. 2000). This is attributed to the fact that almost all the P fed to ruminants is excreted in faeces and there is potential to alleviate P-deficiency

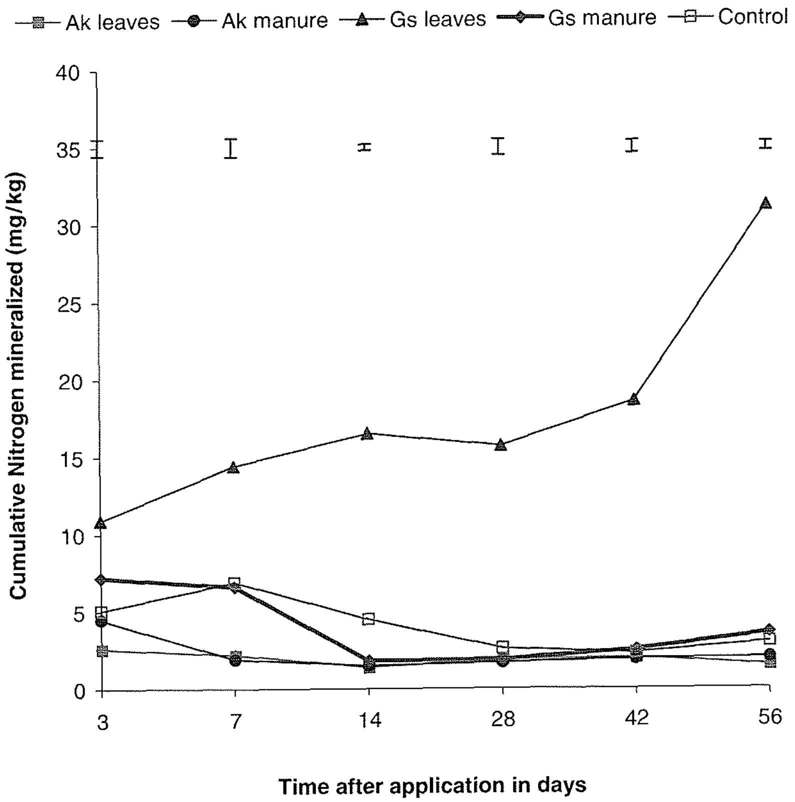

Figure 13.7 Cumulative amount of net N mineralized as affected by tree leaves, manure and incubation priod. Ak: Acacia karro, Gs: Gliricidia sepium, SED: Standard error of difference

application than direct application of tree leaves to the soil. Assessing the costs and benefits associated with the direct application of plant biomass to soil versus feeding plant biomass first to livestock and using manure to fertilizer soil requires information on plant quality, costs and benefits of crops, and livestock production, foregone costs and incomes and financial analysis, and above all farmer's production objectives and market structure.

Conclusion

There are few papers published on polyphenols concentrations in senesced leaves or litter and even fewer papers on fate of polyphenols from plant tissue to their ultimate mineralization and output from the soil ecosystem as dissolved organic carbon or nitrogen or complexation with organic mineral complexes which will stabilize the tannins in the soil. These gaps seriously limit our understanding of how polyphenols interact with nutrient cycling in agroecosytems.

Polyphenols binding to sesquioxides can prevent phosphate sorption and phenolic acids have shown to desorb bound phosphate, thus high polyphenol concentrations might contribute to the maintenance of P availability in highly weathered and acidic soils with high levels of Fe and Al sesquioxides. This area deserves future research. Polyphenols can also retain exchangeable cations (Ca, Mg, and K) by providing sorption sites in highly leached and acidic soils. However, there is little information on the relative contribution of polyphenols to the overall soil cation exchange capacity is available. Well-designed experiments to test the above hypotheses, combined with systematic measurements of quantitative and qualitative polyphenols inputs in a wide range of natural and agroecosystems should be research priorities.

Studies to identify the important types of tannins are needed as they facilitate the development of appropriate and effective manipulation strategies. There is also need to develop simpler field-based methods for determining quantity and reactivity of tannins.

There is need to relate quantity and quality of polyphenols to measures of productivity such crop yields, milk, and meat yield. More information on the trade-offs (biological, social, and economic) between using for crops and for livestock need to be quantified to facilitate more efficient use.

Tannins have both positive and negative effects on N use for crops and ruminants. N-use efficiency can be significantly improved through species selection, mixing of prunings of different quality, state of prunings at use, time of feeding or application to the soil, and interaction of organic inputs with inorganic sources of nutrients. Through this review we have also shown that species which are good for fodder are also good for soil fertility improvement. Since soil ecosystems takes longer to show effects of application of materials of different quality, it may be more efficient to use quicker rumen ecosystem studies to select and screen large numbers of species or provenances for soil fertility improvement.

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Section 4

Towards Better Understanding: Analytical and Modeling Tools for Agroforestry Research

Chapter 14

The Role of Ecosystem-level Models in the Design of Agroforestry Systems for Future Environmental Conditions and Social Needs

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Introduction

Forestry is the art (skill), practice, science, and business of managing forest ecosystems to sustain an ecologically possible and socially desirable balance of forest resources and other ecosystem services and values. Agroforestry[1] could be defined similarly, but in reference to agro-ecosystems and tree-crop-animal resources. When practiced by indigenous cultures, agroforestry has been based on their experience-based wisdom about what works and what does not (Hsiung 1996). However, if a different set of agroforestry values (e.g. a new crop or tree species) and/or a new agroforestry system for which there is little or no experience are to be sustained, this experience-based approach must be supplemented with an understanding of the ecological processes that underlie both the traditional systems and the new set of values. Because social unrest, wars, diseases, natural disasters, and the continuing urbanization of the world's population result in the loss of traditional rural knowledge, the design of future agroforestry systems will have to be based as much or more on an understanding of the processes responsible for production and sustainability of multiple values and environmental services as it has on traditions and experience in the past. When properly implemented, the approach of experience + process-level understanding can capture the benefits of traditional systems but also have the flexibility to respond to the changing needs and desires of individuals and societies, and to changing social and environmental conditions.

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[1] Defined by ICRAF as "a collective name for land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on the same land management unit. The integration can be either in spatial mixture or temporal sequence. There are normally both ecological and economic interactions between the woody and non-woody components in agroforestry.")

S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

In this paper we give some examples of traditional agroforestry systems that we have studied and how they have been impacted by the challenges of an expanding human population and changing human priorities and values. It is our thesis that, because of population pressures and environmental problems, society cannot afford the time to accumulate the experience necessary to evaluate the sustainability and relative efficacy of new or alternative agroforestry systems on a purely empirical basis, especially in the face of risks posed by climate change. Furthermore, space and resource limitations rarely permit empirical testing of the full range of possible new agroforestry designs. Experienced farmers may have the knowledge to guide such changes, but in many cases they have been/are being replaced by younger, less experienced individuals. In many countries where agroforestry has historically been important, disease, the migration of younger people to cities, and social disruptions or political upheaval have interrupted the traditional transfer of experience from generation to generation, furthering the need for process-level understanding to compliment what remains of experience-based knowledge. Although empirical studies and appropriate experience will always be the most believable approach, we argue for the need to understand ecosystem processes as a component of forecasts of the possible consequences of modifying traditional agroforestry practices to meet contemporary and future circumstances. We should develop an approach to integrate the knowledge and experience that is the foundation of traditional agroforestry systems with process-level knowledge gained in part from a western science-based methodology. This integrated approach can provide forecasting and decision support tools that are able to examine the sustainability of alternative agroforestry scenarios within the context of ecological, economic, and social value trade-offs.

In the first two sections of the paper, we explore the three components of science as we understand it, and consider agroforestry science in the context of this conceptual framework. We then describe a family of models that we have developed in the Faculty of Forestry at the University of British Columbia. Initially developed for forestry applications, these ecosystem management models are now equipped for application in agroforestry, and several such applications are underway. We assert that the modeling approach presented here is an effective way of combining traditional knowledge and western science-based disciplinary understanding.

The Three Component of Science

Applied science should ultimately be concerned with providing individuals and societies with the knowledge and tools they need to achieve their aspirations, while maintaining a sustainable relationship to local and global environments. Such lofty goals are overwhelmingly complex. Western science is traditionally broken down along the lines of social and biophysical disciplines, and their sub-disciplines. Unfortunately, each successive level in the knowledge hierarchy makes a progressively smaller contribution to our understanding and management of the overall problem. The result is often a greater understanding about each sub-component but progressively less understanding of its significance to the larger question. To avoid the undesirable consequences of unidirectional reductionism, it is important that agroforestry science incorporates all three of the major components of science: knowledge, understanding, and prediction (Figure 14.1).

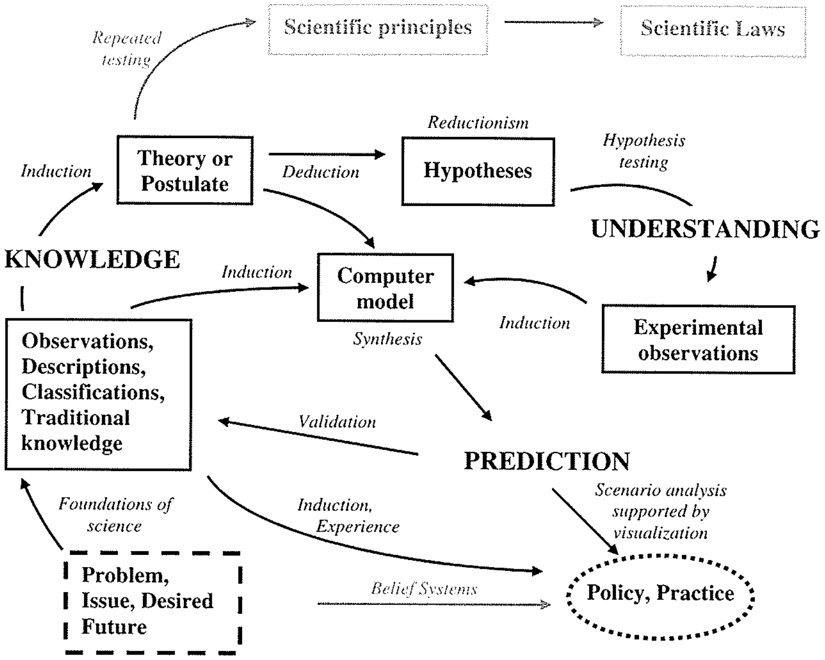

Figure 14.1 The three components of science: knowledge, understanding, and prediction. Knowledge acquisition is driven by the need to resolve a problem, an issue, or to attain some future desired condition. Theories or postulates are derived (by the process of induction), leading to the formulation of testable hypotheses (by the process of deduction), and tests of their validity (the understanding component). Computer models are a mechanism for integrating knowledge and understanding in order to derive predictions of system behavior and future system condition. Predictions, which can form the basis for policy and practice, they should be validated against knowledge and experience. Agroforestry science should involved all three components. (Modified after Kimmins et al. 2005.)

1. **Knowledge**. The first component of the scientific process is the identification and description of the object or system of interest. This is followed by the application of inductive reasoning based on the knowledge gained and from which conclusions about the object or system are drawn. Although conclusions at this stage are generally not critically tested, they can form the basis for developing inductively-based scientific theory and human belief systems. This component of science involves knowing, and knowledge accumulated over time becomes experience. This has been the domain of traditional, experience-based agroforestry. Its utility with respect to designing change in agroforestry is limited by the time required to acquire experience of new and untested agroforestry systems relative to the pace of social and environmental change, something that has been referred to as *future shock* (Toffler 1971). Nevertheless, it forms an important foundation for the design of new systems.

2. **Understanding**. Inductively-derived theories and belief systems need to be tested if we are to have confidence in their validity. The dangers of accepting belief systems or poorly-informed, inductively derived theories about ecosystems is well illustrated in the recent FAO/CIFOR report on the relationship between land use practices and floods (FAO 2005).Testing can involve comparisons between the logical consequences of the theory or belief system and the observed consequences of its application. However, inductively-derived hypotheses about ecosystems are usually complex and consequently may be un-testable because of the long duration and size of the experiments required and the complexity of the factor interactions. Critical testing, therefore, requires that the original theory or postulate be broken down into simpler component parts - the process of scientific reductionism – about which sub-hypotheses are derived by deduction and tested in critical experiments (Popper 1965). This results in an increased understanding of the subcomponents and processes of the object or system of interest, but may do little, on its own, to improve our understanding of and ability to forecast future states of the overall object or system. While this hypothetico-deductive stage is a *sine qua non* of understanding and advancement in science, it is insufficient on its own as the means by which to make forecasts from which to guide the development and management of complex systems such as are found in some types of agroforestry. Hence, much of the research in agroforestry should probably be done at this level, but its full value will only be realized when integrated in the third component of science.
3. **Prediction**. The ability to make accurate predictions is an important part of hypothesis testing in the second (hypothetico-deductive) component of science. However, the scope of prediction at this stage is confined to subcomponents of the original focus of investigation. If predictions are to be made that pertain directly to the original object, issue, or system, they must be derived from a model that integrates the key components of the overall system over appropriate temporal and spatial scales. The resultant model has to be sufficiently complex and of an appropriate scale that its predictions of future states of the system are plausible (see Kimmins et al. 2005). It should be as simple as possible but as complex as necessary - Occam's razor; as simple as possible, but no simpler – attributed to Einstein.

Paradigms of Agroforestry

Beyond the traditional manner in which agroforestry sytems are classified (e.g. agrosilvicultural or silvopastoral systems), agroforestry practices and research can be classified according to the extent to which they integrate the three components of science. In this section, we illustrate how knowledge, understanding, and prediction are all required if science-based agroforestry is to serve the needs of our crowded and changing world.

Agroforestry Based on Historical Knowledge and Accumulated Wisdom

In societies that have undergone limited technical and scientific development, agroforestry systems are based on knowledge and accumulated wisdom (Figure 14.2). Traditional knowledge and experience are critical to the success of the system and are often integrated within the social and cultural fabric of the population through customs, codes of practice, and formal religious beliefs. An example of this type of system is the bamboo (*Gigantochloa* spp.) talun-kebun system of northwestern Java (Christanty 1989; Christanty et al. 1996, 1997; Mailly et al. 1997; Figure 14.2C.).

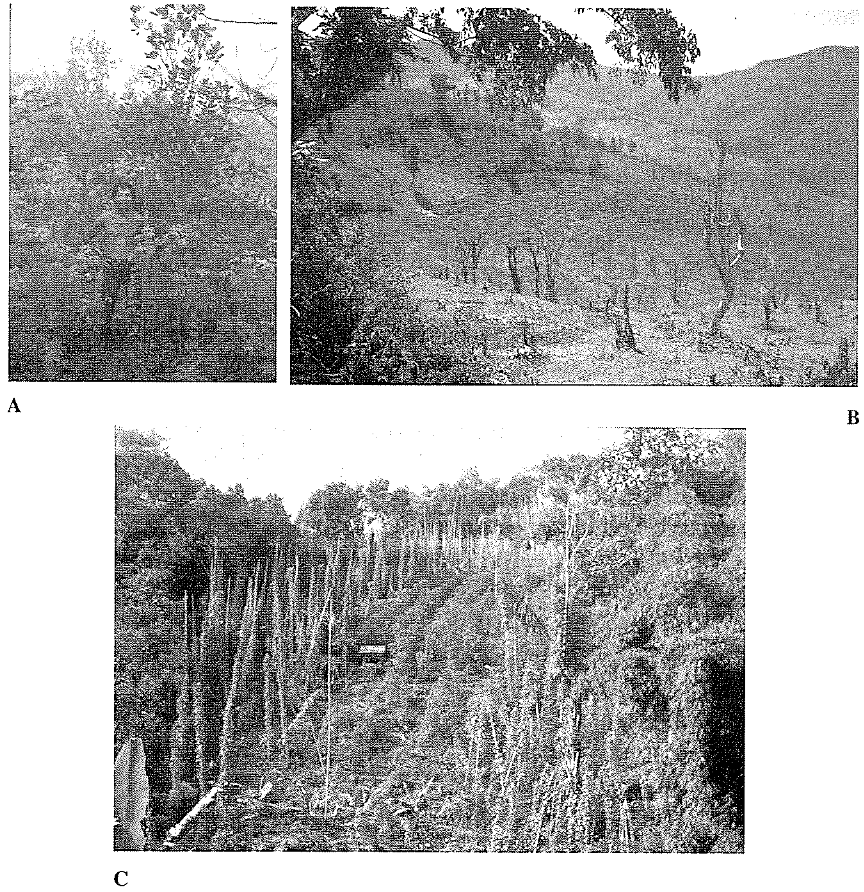

Figure 14.2 Three examples of traditional agroforestry systems based on experience. A. Peasant farmer in traditional homegarden in southeastern Sumatra. B. Swidden agriculture in NE Thailand. Fallow field slashed ready for burning and planting upland rice. C. The talun-kebun bamboo agoforestry system in Java, Indonesia. (Photographs by J. P. Kimmins (A and B) and Linda Christanty (C).)

Based on the belief that "without bamboo the land will die," it served the needs of Javanese hill tribes for many generations. The talun-kebun developed as a shifting cultivation system with a long fallow period. Clearing the forest for crop production on progressively shorter cycles in response to population pressures degraded the soil and permitted the invasion and dominance of bamboo - a disturbance adapted plant. By managing the bamboo in a 6-year or longer cycle (2 years of food crops followed by at least 4 years of bamboo fallow); by including nitrogen-fixing legumes in the food crops and saving ash from burning bamboo slash and forest floor (undecomposed litter) to be used as fertilizer; by composting weeds and plant waste and using this and animal manure as fertilizer; and by incorporating scattered tropical trees (many in the family Leguminosae), the capacity of the ecosystem to produce food products was maintained. These traditional practices served as the basis for a stable and sustainable subsistence agroforestry system because they were well informed by experience, and the size and standard of living of the human population they supported was stable or increasing relatively slowly.

Another example of experience-based agroforestry is the swidden agriculture used by the hill tribes in northern Thailand (the Karen people) to produce a dryland rice crop and a variety of timber and non-timber forest products (Figure 14.2 B). In this system, shrubs, small trees, and the branches of larger trees are hand cut and the slash burned. One year of rice production is then followed by a forest fallow created by the re-sprouting of the trees and shrubs. As the forest fallow redevelops, a variety of other products can be harvested. The success of this system appears to depend largely on the length of the forest fallow (Wangpakapattanawong 2001). The local people are aware that extended cropping will result in severe weed competition and loss in rice production from insects and disease. However, there is pressure from both the government and non-governmental organizations to abandon shifting cultivation on most of the landscape and replace it by fixed-field agriculture over a relatively smaller proportion of the area. The traditional knowledge and experience of the Karen do not provide an adequate basis for evaluation of the suitability and sustainability of the proposed new systems which will require the use of agricultural chemicals with associated environmental and social issues.

A third example is that of homegardens. An informal system of trees, shrubs, herbs, and animals located close to residences, these systems have played an important role in the domestic economies of rural people in many tropical countries (Price 1989). Diverse, energy efficient and producing multiple values, homegardens based on local experience and traditions are an important aspect of agroforestry (Figure 14.2 A; see also Brady 1997).

Agroforestry Based on Scientific Understanding

The success of traditional agroforestry systems bespeaks of a long history of trial and error and of accumulated experience and wisdom. By following established practices and customs, these systems have been successful over many generations. Their success did not depend upon knowledge of the specific processes and mechanisms that sustain them, although in some cases experienced farmers undoubtedly understood some or even many of the processes involved. However, without an understanding of all the major mechanisms and processes that render experience-based systems sustainable, the consequences of change in those systems can be difficult to predict (e.g. Brosius 1990). The talun-kebun system in Indonesia is an example.

The talun-kebun has been replaced in parts of Java by fixed field cash-cropping systems. In these systems, bamboo is no longer a desirable species and manual weeding or herbicides are used to eliminate it and other "weed" species. Bamboo is a key component of the traditional system. Replacing the bamboo with cash crops – tropical fruit and other food crops - may mean that productivity can be maintained only with the addition chemical fertilizers and possibly the use of pesticides. Christanty (1989) studied the ecological mechanisms driving sustainability in this system. She reported that the massive root system of the bamboo prevented erosion in the steeply sloping fields, reduced leaching of nutrients, returned to the surface in litterfall much of the nutrients leached deeply into the soil profile during the cropping period, and provided a substantial input of dead organic matter to the soil in the form of dead fine roots as the upper soil layers in the cleared fields were hand cultivated. Replacement of bamboo by crops that lack such an extensive root system reduces these important ecological functions and threatens sustainability unless the loss is compensated for by increased external inputs.

Wangpakapattanwong (2001) examined the swidden agriculture of the Karen hill people in northern Thailand to elucidate the ecological principles underlying its sustainability (Figure 14.2B). He confirmed that the decline in rice production from extended cropping was due to weed, insect, and disease problems (which the local people are aware of), issues that are controlled naturally by the forest fallow. He also speculated that another key role of the forest fallow was to maintain a coarse soil structure with large, robust peds, and high large pore space. This soil structure is critical in preventing erosion on the sloping fields during the heavy monsoon rains that characterize the region. Soils lacking such structure have higher bulk densities and reduced infiltration rates, which increases surface runoff and erosion. It is thought that the extensive root systems and the above- and belowground litterfall (which sustains an active soil fauna) that develop through the fallow period are critical for the maintenance of soil structure as well as helping to restore soil fertility post-cropping. Replacement of this system by fixed fields without a fallow would not permit these key ecological functions of the fallow to operate, with implications for sustainability and the need to use agricultural chemicals.

Cao (2000, 2003) studied a variety of *Ginkgo biloba*/crop agroforestry systems in eastern China, investigating both intraspecific (*Ginkgo* density) competition, interspecific competition (*Ginkgo*/crops at varying densities), the interactive effects of nutrition, light, and moisture on biomass and carbon allocation in trees and crops, and foliar bioflavinoid levels in *Ginkgo* (Figure 14.6 C,D). He also quantified the changing performance of Ginkgo and crops as the Ginkgo ages across a chronosequence. In the absence of appropriate experience, such production ecology information is an essential foundation for the design of optimum agroforestry systems.

While trial and error could discover optimum designs, this would require a large area of field trials over several cycles of perhaps 25–30 years each, a land commitment and delay that could be avoided by basing new designs on an understanding of the production, population, and community ecology of these systems, as provided in Cao's studies.

Prediction in Agroforestry

Traditional knowledge is an adequate foundation for agroforestry practices and prediction of future yields under stable social and environmental conditions, but not under changing conditions for which experience is lacking. Understanding the processes that determine the productivity and sustainability of an agroforestry system provides a basis from which to adapt experience-based systems to changing social needs and environmental circumstances. As noted above, however, understanding is usually derived from the application of the (reductionist) hypothetico-deductive method which, by definition, tends to fragment the system into individual components and processes. This does not generally provide an adequate understanding of the entire social and biophysical system over entire agroforestry crop cycles, and agroforestry policy and practice based on fragmented science can lead to unexpected and undesirable outcomes. Only when experience (traditional knowledge) is integrated with an understanding of key components and processes (both social and biophysical) is it possible to develop appropriate conceptual models, and forecasting and decision support tools based thereon, for agroforestry.

Predicting the behavior of complex systems is often conducted with computer models. In forestry, historical bioassay models (Kimmins 1988; e.g. traditional growth and yield models) are experienced-based models assembled from large empirical datasets. As such, their predictions are highly believable but only under the circumstances and conditions equivalent to those under which they were derived. They are poor predictors when circumstances change significantly (Assman 1970). A process model simulates the structure and function of a complex system (such as a forest or agroforestry system) directly using mathematical representations of the underlying biological processes that control the behaviour of the system (Godfrey 1983). They have the flexibility to accommodate changing conditions (Korzhukhin et al. 1996), but only if all the key components and processes of the system are represented explicitly (Kimmins 1993). Unfortunately, incorporating enough ecosystem processes to make a purely process-based agroforestry model that will give acceptably accurate predictions under changing conditions can easily results in a tool that is so complex and difficult to calibrate that it is unusable other than as a research tool. One solution is to approach the calibration of the key components of the process model by combining experience-based data sets with understanding of the key processes. This "hybrid" and "backcasting" approach is discussed further below.

Key Components of Ecologically-based Prediction Systems in Agroforestry

The scientific knowledge needed to develop ecosystem-based simulation models applicable in any land-use system, including agroforestry, should include those aspects of the following biophysical components that are relevant for the system being simulated (Kimmins 1993):

1. Production ecology - the relationship of leaf area, leaf efficiency, and carbon allocation to different plant parts (including harvestable crop components) as a function of climate, moisture, light, nutrient availability, and plant nutrition.
2. Population ecology - intraspecific competition for space and resources; the effects of competition (plant density) on individual plant size, carbon allocation, and mortality.
3. Community ecology - interspecific interactions, ecological niches; "overyielding" due to niche differentiation, and mutualistic or symbiotic interactions; "underyielding" as a consequence of antagonistic interactions, herbivory, and niche overlap.
4. Ecosystem ecology - soil physical properties, nutrient cycling, water balance, and hydrology; ecosystem change over time due to management and plant/animal mediated disturbance; interaction of stand and landscape-level processes. Ecosystem ecology generally includes some aspect of climate, microclimate, topography, geology, soils, hydrology, botany, zoology, and microbiology. The possible consequences of climate change scenarios should be considered if the time scales of prediction require it.

Which biophysical components are needed in an agroforestry model will depend on the particular system, the type of predictions required, and the tradeoffs between generality (a model that can be applied over wide areas but with less accurate predictions) and accuracy (specific predictions that pertain to local conditions).

The FORECAST Approach to Modeling Agroforestry Ecosystem Management

A large number of agroforestry models have been developed. This modeling diversity stems from the fact there can be no single "best" model. Different applications of modeling in agroforestry vary in terms of desired model performance and the data available for calibration and validation. Examples of agroforestry models and their application can be found on the Agroforestry Models Users Group[2] or the International Centre for Research in Agroforestry (ICRAF)[3] websites.

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[2] http://www.edinburgh.ceh.ac.uk/tropical/agrofore.htm

[3] http://www.icraf.cgiar.org/sea/agromodels/agromodels.htm

Here, we describe the FORECAST family of ecosystem management models, the hybrid simulation approach on which they are based, and their applicability to agroforestry systems (for further information, see Kimmins et al. 1999; Seely et al. 1999, 2004). These models simulate the management of complex systems by integrating empirically-based knowledge with representations of key ecological processes. The basic approach ("backcasting"; mining empirical data to obtain estimates of process rates) is to use the empirical input data to estimate the rate at which key ecosystem processes (e.g. efficiency of light capture by each species, nutrient cycling, and nutritional regulation of growth) must have operated to produce observed trends in ecosystem process variables, productivity and biomass accumulation (see Kimmins et al. 1999; Seely et al. 1999, for further details of this approach to the calibration of a process model). These rate estimates, obtained in the "setup" stage, are then used to drive the model's simulations, which in turn are used to project future conditions given a particular management and/or natural disturbance or environmental change scenario.

Figure 14.3 shows the overall file structure of the FORECAST model. Empirical (historical bioassay) data are entered into the setup input files. These data are processed by the setup programs to create the simulation rules and estimates of process rates used in the ecosystem simulation module. FORECAST provides the user with copious graphical output in the setup phase with which to assess the simulation rules and how faithfully they represent the empirical input data. The user can chose any combination of herbs, shrubs, trees, and bryophytes, managed under a wide variety of management scenarios. The simulation module provides a rich set of graphical and tabular assessments of the model's forecasts for diverse ecosystem and management variables. These help the user to assess the model output. To facilitate the analysis of ecosystem production, FORECAST can be operated at different degrees of complexity - as a light-only model (with nutrient cycling and nutrient limitation disabled), or with both light and nutrient cycling/limitation/competition enabled, or with light, nutrients, and moisture represented. The present version of FORECAST is a non-spatial model and so it works best when the spatial distribution of vegetative components in a given "layer" (canopy, shrub, herb, etc. is more or less homogenous. Figures 14.2 and 14.6 show examples of some agroforestry systems that are being assessed using FORECAST. A climate change component of the model has been added.

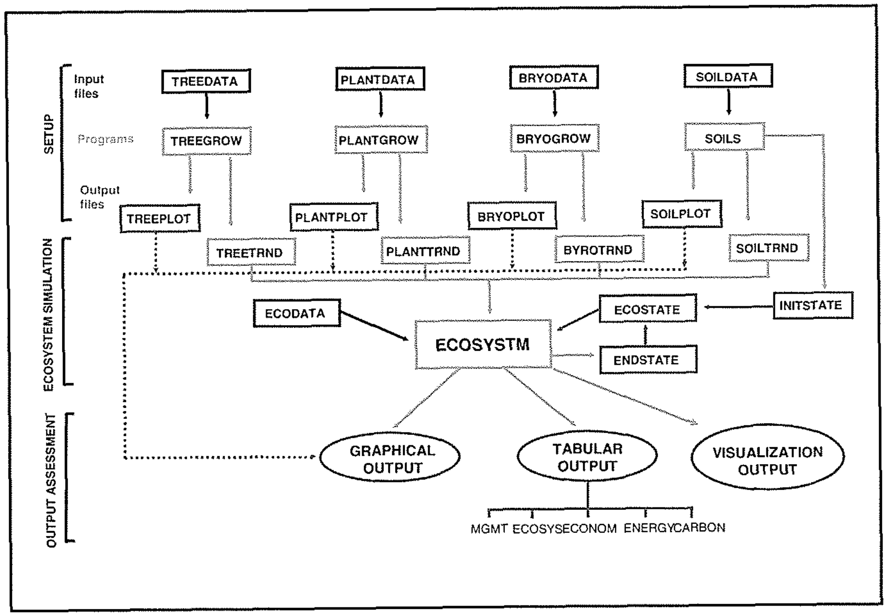

Figure 14.3 Basic file and program structure of the hybrid simulation ecosystem management model FORECAST. Data describing tree, shrub, and herb growth in the past and data on certain process rates and ecosystem conditions (experience-based or "historical bioassay" data) are entered into the setup files. From these data, rates of key processes that are the drivers of the ecosystem process model are calculated. Conditions at the start of a simulation run – soils and vegetation – are created by simulating the history of land use for the ecosystem in question. Alternative ecosystem management and/or natural disturbances are then simulated with graphical, tabular, and visualization outputs. The model is provided with a user-friendly interface FORECAST NAVIGATOR.

Scaling Up in Agroforestry

Agroforestry often involves dynamic spatial relationships. To accommodate this, FORECAST has been extended to a spatially explicit model. This can simulate plant development and ecosystem processes in interacting grid cells (that are as small as 10 × 10 m) within a framework that can accommodate up to 2 million cells (for a total area of 2000 ha). In this Local Landscape Ecosystem Simulator (LLEMS; Figure 14.4) cells are clustered at the start of a run into polygons on the basis of a series of attributes (vegetation structure, density, species composition, age, soil condition, and others). As the simulation proceeds, individual cells may get transferred to other polygons as the developing vegetation changes light conditions or ingress of crops, weeds, or trees changes the vegetation. Management actions such as a harvest, planting or fertilization also cause a subdivision of affected polygons to maintain them within user-set levels of heterogeneity. Cells are updated annually or on shorter time steps. This approach permits very detailed spatial process ("bottom-up") simulation over relatively large areas ("top-down") as well as maintaining flexibility in the face of management or natural disturbance. Natural regeneration can be simulated as a consequence of seed dispersal within and between polygons. In agroforestry applications this would represent invasion of "weed" or other non-crop vegetation that requires management inputs.

LLEMS is well suited to many agroforestry applications since it can represent trees, shrubs, herbs, the independent management of each of these plant life forms and species within life form, site-level management treatments, and the actions of herbivorous animals. It can represent the interactions between rows of trees and

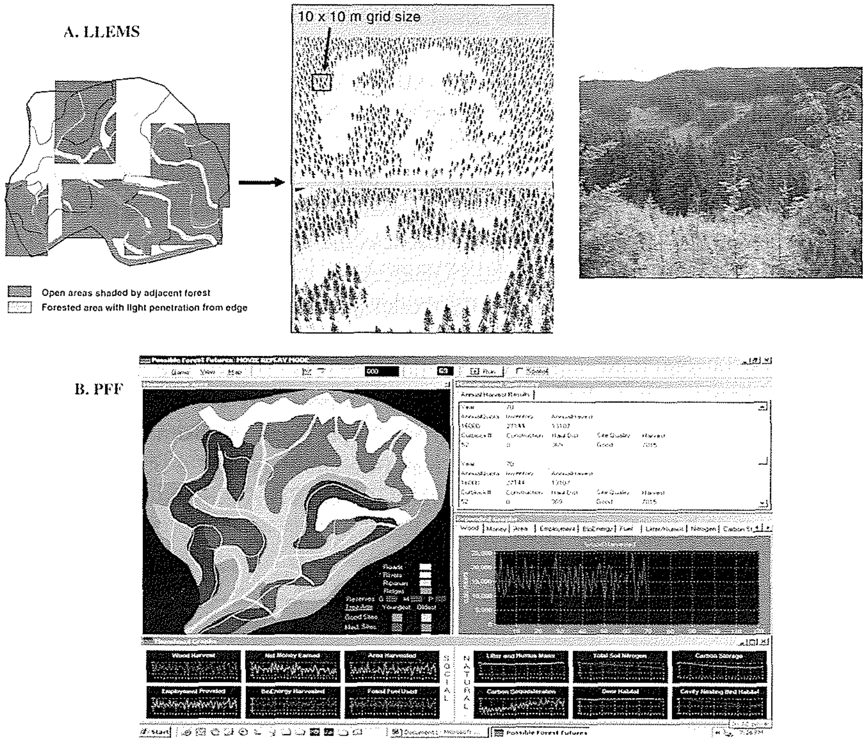

Figure 14.4 A. Plan map and oblique visualization output from the Local Landscape Ecosystem Management Simulator (LLEMS); hypothetical example. Also shown an example of variable retention forestry system in coastal British Columbia that is the current focus of this model. B. Possible Forest Futures (PFF) screen image showing landscape map and thumbnail graphs of simulated time trends in a variety of ecosystem and management variables. This small watershed model can equally well be used as a small landscape agroforestry model.

crops in alley farming or other spatial arrangements of trees and crops. Figure 14.5 shows potential landscape-level agroforestry applications for the LLEMS model.

Some agroforestry applications require models that can simulate the effects of local events across even larger spatial scales (10,000 ha, and more). For example, conversion of the talun-kebun bamboo system to cash crops has necessitated the use of chemical inputs to maintain productivity and control undesirable plant and insect species. Residues from these chemicals are transported downslope in runoff water and may contaminate lowland rice paddies and water supplies (see Figure 14.5B). A local, stand, or field-level solution has triggered a non-local landscape issue. Our small watershed model, Possible Forest Futures (PFF), is designed to simulate problems of this nature by integrating land-use systems over watershed landscape scales. Similar to LLEMS in terms of polygon structure and interaction (minus the detailed light profiling; see Figure 14.4A), PFF includes a hydrology model and can

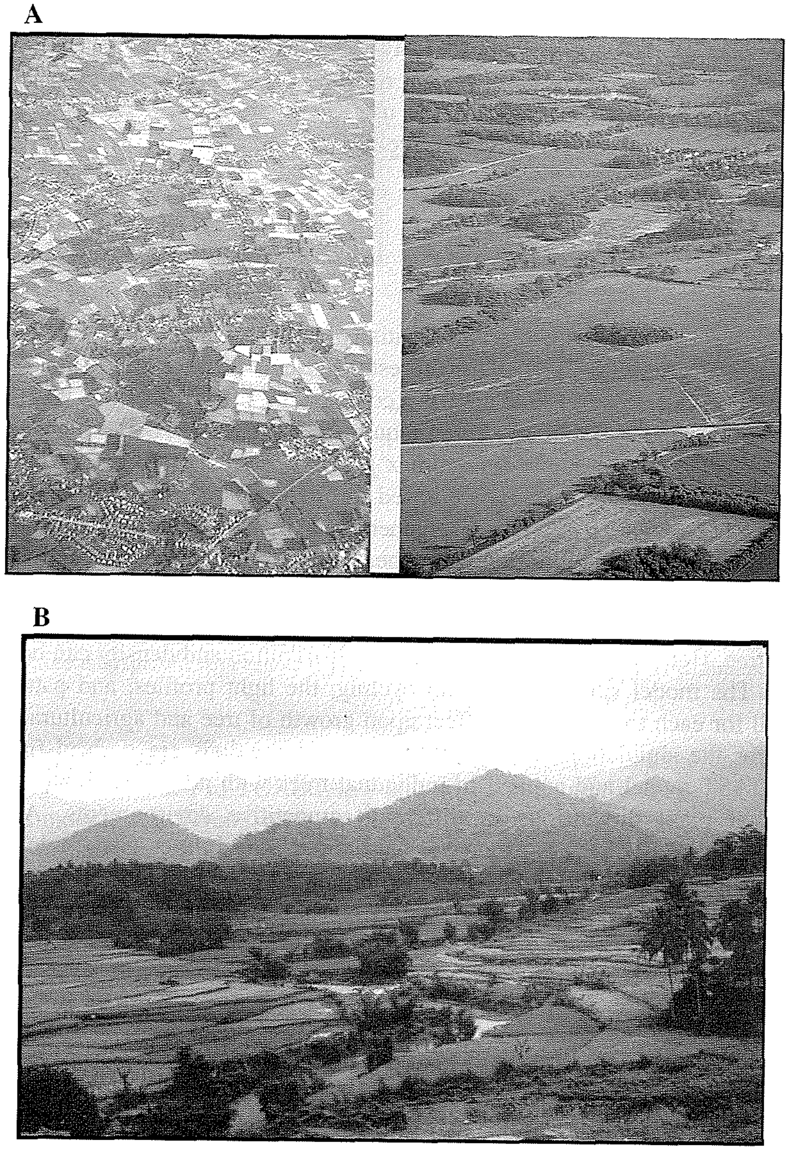

Figure 14.5 A. Previously forested land in Europe converted to agriculture and interspersed with forest. These small landscape units can be simulated by the LLEMS or PFF models. B. A rice paddy lowland near Bandung, Java, Indonesia, with the hill region in the background where the bamboo talun-kebun agroforestry system described in the text is practiced. This larger landscape can be simulated using the PFF model or by linking FORECAST to a large landscape model.

track road development. The model also includes an extensive output list of economic costs and returns, productivity, and carbon budgets (Figure 14.4B). Because it is an ecosystem management model that can simulate most aspects of agroforestry systems, PFF can also be used to examine land use patterns that include agroforestry and agriculture as well as forestry.

Scaling Down in Agroforestry

We are developing an individual tree, spatially explicit application of FORECAST that will provide an analysis of agroforestry systems at very fine spatial scales. Tropical homegardens in which there is a complex intermixing of trees, shrubs, and herbs (e.g. Figure 14.2 A; Price 1989) requires experience of how to manage such spatially and ecophysiologically complex systems. Farmers in areas that employ homegardens have this experience-based knowledge, but this is threatened as cultures and societies change or as intergenerational transfer of traditional knowledge is disrupted by social and/or political upheavals. Some contemporary agroforestry systems may also require understanding of tree-crop interactions at the individual tree level. In the FORCEE model, the spatial coordinates are known for each individual tree. Hence, any configuration of tree distribution and density can be represented. The model simulates nutrient cycling, the light profiles, and patterns of litterfall for each tree, and their effect upon growth of tree and agricultural crops. Rules for the simulation of plant growth and interactions are derived from the FORECAST model and applied to individual trees with additional input data on individual plant dimensions in different competitive environments. As with FORECAST, FORCEE has extensive management capabilities (see Table 1) and produces a rich array of output variables. Figure 14.6 A, B shows an example of stand growth visualization output derived from FORCEE and in Figure 14.6 C, D are real-world examples to which the model can be applied.

Future Considerations in Modeling Agroforestry

Climate change and its possible effects upon ecosystems have received considerable attention (Houghton et al. 1990). If the potential of agroforestry is to be realized and maintained, this issue must be addressed whenever projections are made regarding the future productive capability of a given system. With respect to model development, it would be desirable to simulate the response of key ecosystem processes (e.g. photosynthesis, phenology, decomposition) to variations in daily air temperature and occurrence of frost, daily precipitation, and elevated CO_2 concentrations. Response functions for the main drivers of ecosystem production (see above) should be included with consideration for the fact that many are likely to be species-specific and exhibit interaction of factors. Climate change capability is currently being added to FORECAST and will consequently be available in the derived models at different spatial scales.

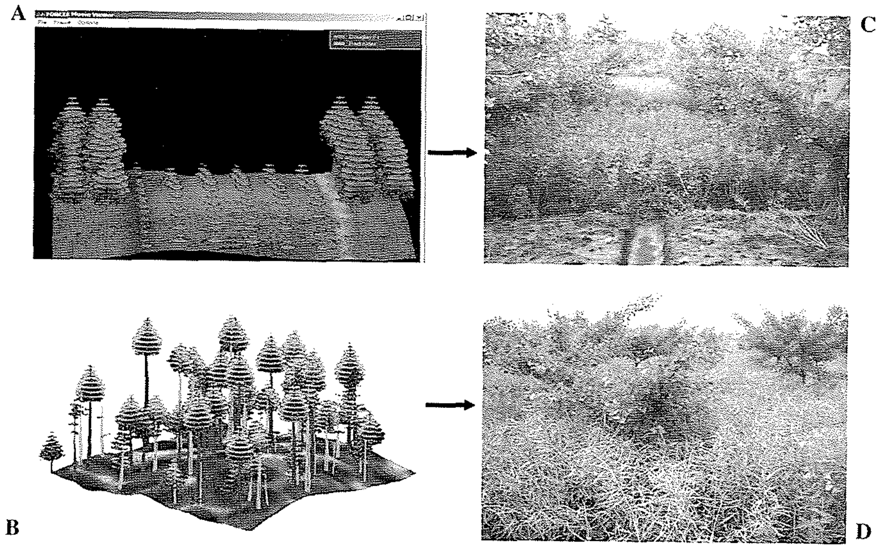

Figure 14.6 Examples of output from the individual tree FORCEE model showing alley cropping (A) and an evenly-dispersed tree grouping (B). Real-world analogues are shown in C, a Gingko (*Ginkgo spp.*)-broad bean (*Vicia faba*) alley-cropping system, and in D, uniformly-distributed Gingko trees interspersed with canola (*Brassica napus*). (Photographs by J. P. Kimmins.)

The question of climate change effects on ecosystems is complex and fraught with uncertainty. This relates both to uncertainty as to what future climates and weather patterns will be, and uncertainty about how organisms, ecosystems, and natural disturbance agents will respond. Depending on the limiting factors in specific ecosystems and the predicted atmospheric changes, effects may be positive, negative, or neutral. This emphasizes the need to move away from a dependency on empirical, correlation-type models to mechanistic, process-based models. However, as noted above, there is merit in combining these two approaches into hybrid systems. The extent of our knowledge and ability to represent what we do know in process models continues to be limited, and combining representations of key processes with empirical models will probably be the most effective strategy for some time to come. Combining traditional wisdom about agroforestry with a western science-based understanding of key processes (unless of course the traditional knowledge already incorporates this *explicitly*) is suggested as the optimum approach.

No attempt to review the many possible effects of climate change is made here; that is well beyond the scope of this paper. Similarly, extensive review of the literature on modeling agroforestry ecosystems was not an objective of our contribution.

Conclusions

Our assertion that forecasting the future of agroforestry systems (particularly new untested systems) should incorporate past experience and traditional knowledge honors the long history of agroforestry and the accumulated wisdom about it. In the face of continued increase in human population and per capita standards of living (i.e. in total human pressure on global ecosystems) and in environmental change (e.g. climate change) it is likely that both traditional agroforestry and western agriculture will also change. Unlike in annual crop agriculture, the empirical testing of new agroforestry systems over several cycles to assess their efficay and sustainability is not possible; the tree component adds a time dimension that reduces the value of simple adaptive management strategies. Consequently, there is a need for scenario assessment tools that explicitly incorporate our current understanding of the key processes that underlie the sustainability of agroforestry systems. We believe that the combination of experience with process-level understanding into hybrid systems is the most effective way to develop appropriate decision support tools.

Decision support tools in forestry and agriculture have often been single value systems: timber volume or crop mass, for example. We believe that the future will focus on multiple values for these systems: crop yield, employment, economics, maintenance of soil functions, non-crop vegetation, wildlife habitat, hydrology, carbon and energy budgets, management challenges, pathogens, and other factors. While no single model can incorporate all values, the use of ecosystem-level models permits the user to address many of the biophysical variables, and, in combination with social sciences, to interpret these in terms of several social values and environmental services.

Forestry and agroforestry have generally focused on stand and field-level issues. These are important. However, the values of specific stands and fields are affected by their landscape context. In ecology, forestry, and conservation, it is increasingly recognized that management and conservation of local ecosystems must be considered in the context of local and sometimes even regional landscapes. Most landscape-level models lack representations of stand or field-level ecological processes and other details. There is a need to scale up from small to larger spatial scales, especially as urbanization and rural de-population may lead to larger rural management units.

Our conclusions from this assessment, which have guided our modeling, are that ecosystem management decision support tools should be ecosystem-level, as simple as possible but as complex as necessary for the system in question, multi-value, and able to address a variety of spatial scales. Because agroforestry systems may be either spatial or temporal mixtures of tree and non-tree crops, these decision support tools should be capable of representing the spatial and temporal scales involved. We also feel that the difficulty in using most computer models renders them of little value to most policy makers and farmers. Agroforestry models should have user-friendly interfaces that facilitate their application by a range of potential users who vary in their levels of understanding of such tools. The development of the FORECAST family of models has been guided by these conclusions.

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Chapter 15
Radiation Availability in Agroforestry System of Coffee and Rubber Trees

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Introduction

Arabic coffee (*Coffea arabica* L.) originates in the high lands of Southern Ethiopia, close to the equator, at latitudes 6 to 9° N, longitudes of 34 to 40° E and altitudes of 1400 and 1800 m. This region has a dry season that lasts for 3–4 months, and the annual precipitation ranges from 1200 to 2000 mm throughout the year. Temperature varies from 18 °C to 22 °C. In this area, coffee plants always grow under conditions of shade in the tropical forest (Krug, 1959; Kumar, 1979).

The discussion about shade-grown coffee has been going on for over a century (Lock, 1888; Guiscafre-Arrillaga, 1957; Beer et al. 1998), and still today many of its aspects are being researched, such as the intensity of shade, its management (Beer et al. 1998); the use of fertilizers (Farfan and Mestre, 2004); the quality of the fruit/bean and of the beverage (Muschler, 2001); etc. Kimemia and Njoroge (1988) state very clearly that the use of shade trees in coffee plantations is historical, but more information is required about the differences and the physiological implications of growing coffee in the shade or in sun. Yet, the same authors pointed out the need and great importance of serious research about shade-grown coffee using trees of economic value.

Coffee is widely grown around the world (Evanoff, 1994). In Latin America, there are commercial plantations ranging from Cuba (latitude: 22° N) to the State

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

of Parana, in Brazil (latitude: 26° S). In Brazil, coffee is economically cultivated under full sun condition. Even in Colombia only about 37% of the coffee cultivated is shade-grown; most of the trees are of the *Leguminosae* family, particularly *Ingá* sp., *Albizzia* sp., *Erythrina* sp., and *Leucaena* sp., and the spatial distribution of plants is not well defined (Farfan and Mestre, 2004).

Coffee cultivation as a monocrop may present problems such as over-production, which can lead to plant stress, mainly during the first few years. This problem naturally decreases later with self-shading (Voltan et al. 1992). Siebert (2002) indicates that the percentage of shade affects coffee production, regardless of the type of shade used. The intensity of solar radiation over the crop influences the photosynthetic structure. The level of light can modify the structure of the leaf during its development. Higher light availability may cause leaf thickness, increases on specific leaf mass, epidermis and parenchyma, and total cell number (Esau, 1977). Fahl (1989) verified that sun-grown coffee had thicker leaves and an increased cell density in comparison to shade-grown coffee. This adaptation mechanism has been reported in other plants. In bean plants, for instance, a decrease on specific leaf area (SLA) has been observed when there is an increase in radiation (Righi, 2000).

Voltan et al. (1992) studying the epidermis of coffee grown under different radiation availabilities, observed that the number of stomata decreased linearly as the radiation level decreased, although the stomata size did not change significantly. Alvim (1960), analyzing the photosynthetic rate and stomata conductance in *Coffea arabica* grown under full sun and in shade conditions, observed that stomata conductance and the photosynthetic net rate were higher in the shade. In Kenya, it has been demonstrated that coffee photosynthesis is higher under low light intensity. The total daily assimilation in the shade was higher than in the sun. *Coffea canephora* generally presents a lower CO_2 fixation rate than *Coffea arabica*, with some genetic variation between cultivars, which can contribute to indicate which genotype is better suited to the Agroforestry System (AFS) (Kumar and Tieszen, 1980).

The presence of trees in the production system alters the radiation balance; air temperature, and wind behavior in the area under its influence (Brenner, 1996; Monteith et al. 1991). The multiple effects of these microclimate changes alter the energy balance available to the environment, leading to changes in water use, yield, and plant cycle.

The plant canopy structure is related to the spatial distribution of its organs above the soil surface (Campbell and Norman, 1989). Plant canopy has an important role in growing and productivity. The canopy architecture plays an important role in defining the distribution of branches and leaves, which alters the interception of available radiation and its use. Efficiency of radiation use is affected by the photosynthetic rate per unit leaf area (Bernardes, 1987). Leaf area index (LAI) and its duration, are the most important factors used to define the dry weight and growth of the plant (Bernardes et al. 1996). Russell et al. (1989) addressed in detail the canopy characteristics and its relation to the environment.

Environmental factors and quantification of plant behavior can be aggregated in mathematic models to improve its practical and scientific use. Mathematic models, as well as the previous research planning, are more important to AFS than to monocrop systems. The pure experimental focus in agrosilviculture is extremely expensive due to: (1) tree longevity; (2) the size of experimental plots; and (3) high variety of possible distribution of plants along time and space. Therefore, it is necessary to perform an evaluation of previous literature and to develop (and improve) mathematic models, to test the hypothesis beforehand (Bernardes, 1993). While the development of a complete model is the long-term goal, the individual module process, which is temporary, plays an important role not only for understanding AFS, but also for predicting its performance (Bernardes, 1993). The mathematic model proposed by Goudriaan (1977 and adapted by Bernardes et al. (1998) Equation 1) account, with good precision, the solar radiation values to crops in field conditions (Righi, 2000), and can be important to help quantify the availability of solar radiation in an AFS.

$$I_r = \frac{I_0}{2}\,\mathrm{sen}\left(\mathrm{arctg}\left(\frac{d - \frac{c_w^2}{d}}{H_r} + D\right) + 1\right) \tag{1}$$

where,

I_r = daily radiation (MJ m^{-2}) that reaches the canopy of the intercalary crop; d = distance from the row of shading trees (m); I_0 = daily radiation (MJ.m^{-2}) on a horizontal surface above the tree canopy; c_w = tree canopy radius (m); D = declivity of the ground (radians); H_r = relative tree height (m), obtained through the equation (2)

$$H_r = H_a - H_{ci} \tag{2}$$

where,

H_a = tree height (m); H_{ci} = height of intercalary crop (m).

A better understanding of the ecophysiological interactions in AFS, originates new scientific questions other than the improvements to crop management. The technological improvement results in better yield, leading to the adoption of AFS by a larger number of rural producers. The increase in crop diversity gained with the introduction of trees of multiple use, such as rubber trees, can lead to a sustainable production.

Understanding how the AFS uses the resources available is essential to determine the combination of species, distribution of the plants, density, and the management best suited for different locations. The study of harvest resources in an AFS can be useful to the analysis of crop performance under several climate and management conditions (Ong et al. 1996, Willey and Reddy, 1981). Many of the benefits of the interaction between trees and crops, such as nutrient recycling, higher production of organic matter, differences in root depth that result in higher absorption of water and nutrients and tree protection against soil erosion and wind, are less obvious and not thoroughly reported (Ong et al. 1991).

When there is an increase on the amount of radiation available, there is also an increase in the performance of several crops, which leads to a higher production of dry matter in a linear correlation with the intercepted radiation (Righi, 2000). Russell et al. (1989), modeling the dry matter production in uniform crops, considers that this is almost in direct proportion to the energy intercepted by the canopy. Beer et al. (1998) reports that, when there is no nutrient limitation, the growth of coffee shows direct and positive correlation with the level of radiation. Farfan and Mestre (2004) observed a similar inverse correlation between the percentage of shade and coffee production, in other words, the higher the percentage of shade, the lower the production. Caramori et al. (1995) observed a quadratic solution for the production of coffee, related to the distance between the trees. Watson (1958) had already observed that net assimilation rates decrease almost linearly with the LAI, which explains the proportionality between growth and LAI (Russell et al. 1989). The latter authors consider that the interception of light by the canopy depends on (i) its structure and (ii) the relation of its production of dry matter per intercepted radiation unit. This type of analysis, although very frequent in monocrop studies (Pereira, 2002; Confalone et al. 1997), is not often reported considering such variables in AFS. Although the physical variables are relatively simple to measure, it is very complex to elucidate how these changes affect the crop in the under store (Corlett et al. 1987).

Šesták (1981) considers that the relation between dry matter and radiation may change along the plant's life, probably due to ontogenetic changes in the canopy, but also due to drain performance on the photosynthetic rate.

This study aims to evaluate the growth of coffee plants (*Coffea arabica* L.) in an alley AFS of rubber trees (*Hevea brasiliensis* Müell. Arg.), under different light availabilities, and to evaluate the model adapted by Bernardes et al. (1998) to estimate the radiation available to the under store crop.

Material and Methods

The experiment was conducted in the experimental field of the Department of Crop Science of the Escola Superior de Agricultura "Luiz de Queiroz," University of São Paulo (ESALQ/USP) in Piracicaba-SP (22°42′30″S, 47°38′00″W – at an altitude of 554 m) during the year 2002. The rubber tree field was planted in 1991 at a spacing of 8 × 2.5 m, with seedlings, in plastic bags that were grafted with two mature leaves. All the experimental blocks consisted of trees from the same clone – PB-235. Coffee was planted at a spacing of 3.4 × 0.9 m during the first half of January 2001, underneath the rubber plantation, in an interface with the trees and in monocrop. The cultivar used was Obatã IAC 1669–20 – Mundo Novo. The seedlings were 9 months old and derived from direct seeding in plastic bags in a nursery with an adequate screen cover.

The land, with approximately 0–1.5% slope, consists of structured eutrophic Terra Roxa, with moderate A-horizon and clayey-textured, of the American classification Kandiudalfic Eutrodox. The soil fertility and the irrigation system set up in the trial area prevented limited growth and development of plants other than those deriving from the experimental treatment. In developing the coffee plants, soil analysis was performed for necessary amendments.

The experiment was conducted in four blocks with 11 treatments – distance from the edge of the trees – and in monocrops planted within the same spacing, weed-free and with no interference from the rubber trees, 50 m away. The 11 treatments included tree distances measured from the first row of rubber trees interfacing with the coffee plantation (zero distance). Negative distances refer to plants on the inside of the rubber tree plantation and the positive distances refer to the distance towards the monocropped coffee. Thus, the treatments used were the distances of −13.7; −10.3; −5.7; −2.3; 1.5; 4.9; 8.3; 11.7; 15.1; 18.5, and 21.9 m from the trees edge and in monocrop (Figure 15.1). In each position 12 plants per distance were evaluated. The first row of rubber trees interfacing the coffee crop represents double rows of trees in an alley-cropping agroforestry system.

Drip irrigation was used in the coffee plantation. The evapotranspiration was estimated by means of a Class A tank, of the Main Meteorological Station of the Department of Exact Sciences, ESALQ-USLP, located next to the experiment. The irrigation depth was calculated according to the method proposed by Villa Nova and Sentelhas (1999).

For the evaluation of dry matter, three coffee plants, from each of the following positions: −13.7; −5.7; 1.5; 4.9; 8.3; 15.1 m and from the monocrop, were harvested and dried in a forced-draught oven at 75 °C.

Each coffee plant had the total leaf area calculated by counting the number of leaves and multiplying that value by the average leaf area. It was observed that the leaf area corresponds to 68% of the rectangle calculated based on its size. So, coffee LAI is calculated based on the plant's canopy projection. Other coffee plants

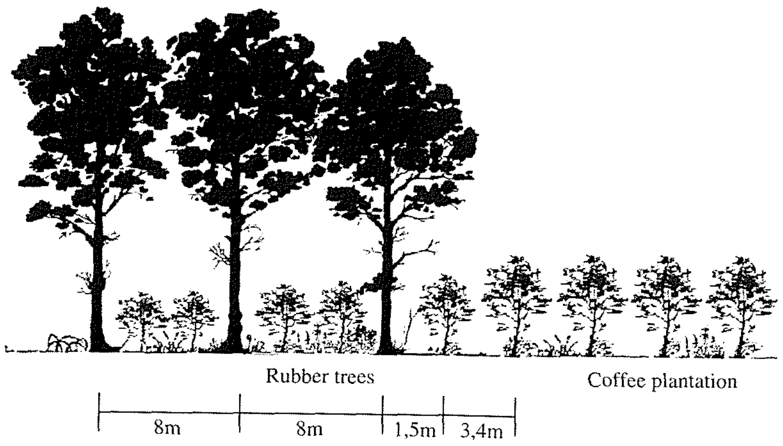

Figure 15.1 Cross-section of the experimental field showing the distribution of rubber trees and coffee plants

characteristics such as height, stem diameter at 5 cm from the ground, stem height, and canopy diameter were measured directly in the same period. The distance from the highest canopy point to the ground was considered the plant height, while the distance between the lowest branch intersection to the ground corresponds to the stem height. The specific leaf area (SLA, m^2 kg^{-1}) was obtained by dividing the area of 10 leaves, randomly sampled, with three replicates per row, by the value of their constant weight after being dried at 75 °C in a forced draught oven.

The characteristics of the canopy of the coffee plants were evaluated according to the following methodology, as proposed by Leong (1980): (i) canopy height, the difference between the heights of the plant and of the stem; (ii) canopy percentage: canopy height divided by plant height multiplied by 100; (iii) canopy opening: average canopy diameter divided by plant height multiply by 100; (iv) canopy filling rate: the quotient between the average diameter and the canopy height, which indicates its rounding; (v) canopy projection: the average diameter of canopy divided by stem diameter multiplied by 100; (vi) canopy volume, which was calculated considering a conical shape; (vii) leaf density: the quotient between total leaf area and canopy volume.

The shading trees were measured using a Haga altimeter that measures the height through ipsometry, and the canopy diameter was measured with a tape in order to evaluate the radiation available to the intercalary crop as described on equation 1.

The light availability to coffee plants was continuously measured through solarimeter tubes (TS-UM-3, Eijkelkamp), at the same evaluated positions, and connected to a data logger (Delta-T Devices). This data were used to evaluate the mathematic model (equation 1).

Results and Discussion

Figure 15.2 presents the solar radiation data collected between October and November, 2002. Each point refers to the integral solar radiation available (MJ m^{-2} day^{-1}). The radiation available to the coffee plants under different conditions – distance between the crop and the border trees: (inside) –13.7; –10.3; –5.7; –2.3 m; (next to the rows) 1.5; 4.9; 8.3; 11.7; 15.1; 18.5; 21.9 m – in percentual terms were, respectively, 25%; 30%; 35%; 40%; 45%; 80%; 90%; 95%, and approximately 100% in the three farthest distances.

Figure 15.3 shows the fraction of radiation available, and the estimate radiation obtained by using the mathematical model (Equation 1). Such model can only be used when the tree canopy is not completely closed (Goudriaan, 1977). This way, only the radiation available to coffee plants placed beside the rubber trees was simulated. The radiation available (transmitted fraction) to plants under the closed canopy can be calculated using the Monsi and Saeki (1953) equation, derived from the radiation extinction law by Beer-Bouguer-Lambert (Vianello and Alves, 2000). This equation can be used to estimate the LAI of plants under different growth conditions as proposed by Villa Nova et al. (2003). It was observed that the model met the values obtained in several days. These results agree with those found by

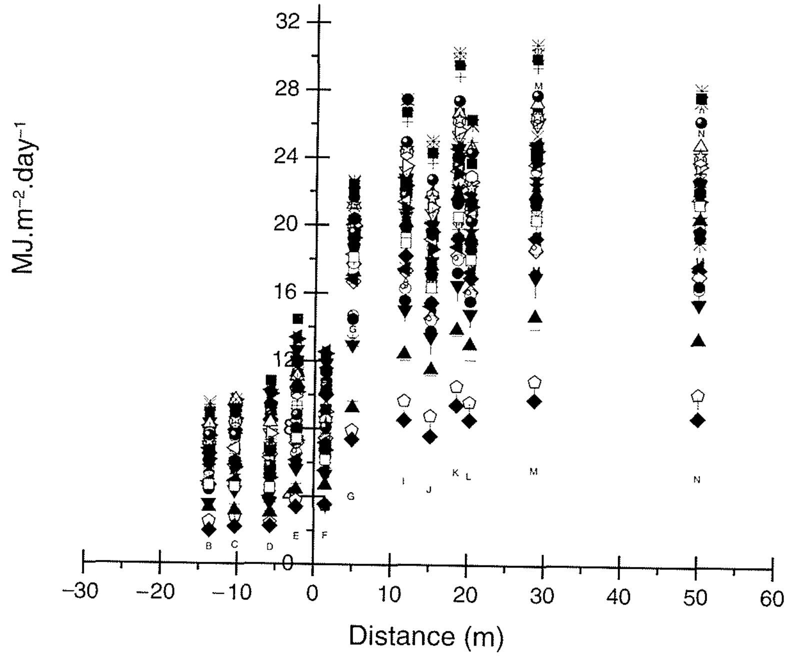

Figure 15.2 Radiation available (MJ m^{-2} day^{-1}) to coffee plants evaluated using a tube solarimeter (TS-UM-3, Eijkelkamp) along the distances between from trees. Negative distances refer to the inside of rubber plantation. Each point refers to integral radiation available along a day

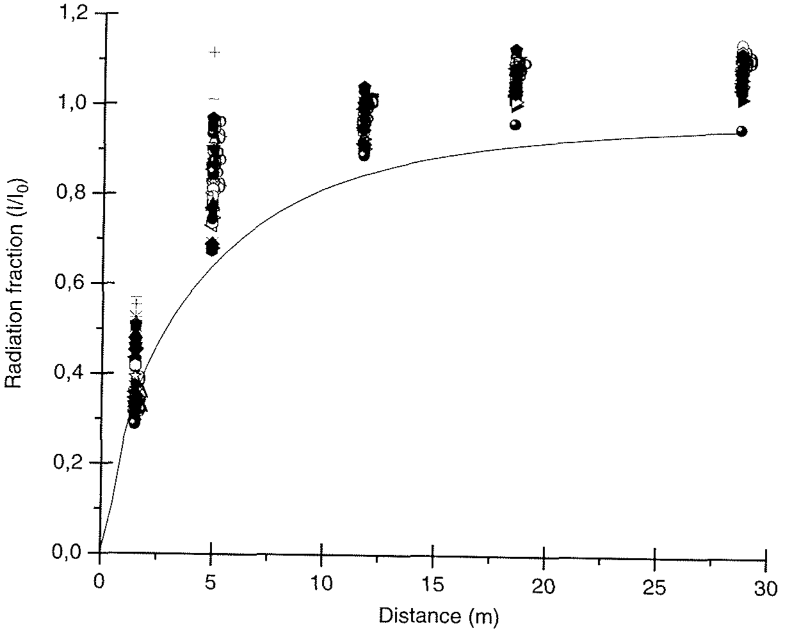

Figure 15.3 Radiation fraction available (I/I_0) to coffee plants considering the distance from shading trees. Line refers to mathematic model calculated values

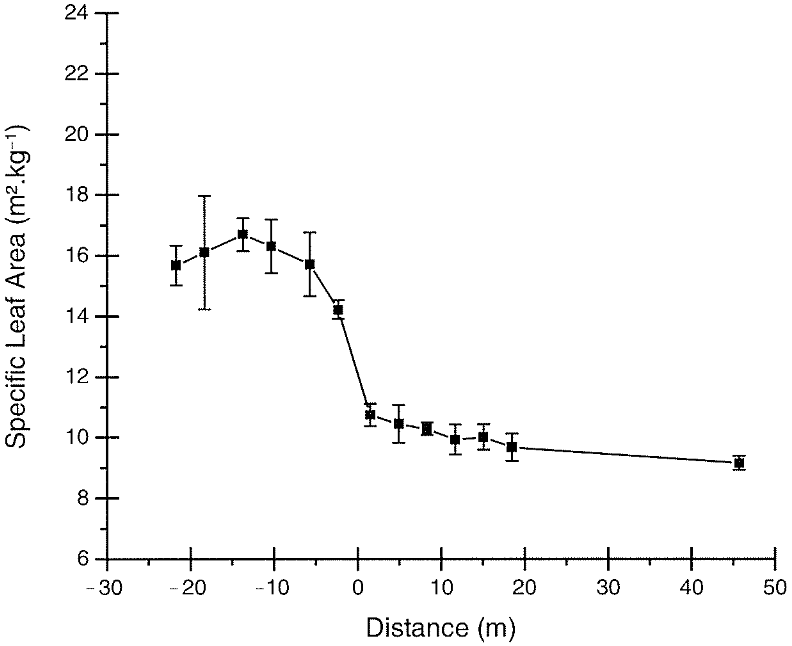

Figure 15.4 Specific leaf area (m^2 kg^{-1}) of the coffee plants in respect to the distance from the rubber tree plantation. Negative distances refer to the inside of rubber plantation

Bernardes et al. (1998) and Righi (2000), who observed that the measured values were approximate to the estimated values in an alley AFS lined with rubber trees and soybean, and another of rubber trees and beans, respectively.

Although coffee plants present a clear tendency to show an increase in the specific leaf area (SLA, m^2 kg^{-1}) under conditions of shade (Figure 15.4), it was not sufficient to equal the total leaf area (TLA) to those of coffee plants grown under higher light availability. The higher SLA value obtained (16.69 m^2 kg^{-1}) was approximately 80% higher than the lowest value obtained (9.17 m^2 kg^{-1}), in which case the plants received the total radiation available (plants in monocrop). Such adaptation has often been observed and reported by several authors (Righi, 2000; Bernardes et al. 1998; Ong et al. 1996; Evans et al. 1988; Esaú, 1977; Pereira, 2002) as one of the main reasons for the success of plants under low light conditions.

It is interesting to observe that, despite the extreme difference between the total leaf areas obtained (from 5370.60 to 22617.87 cm^2 – about four times larger) (Figure 15.5a), LAI was similar in each of the plant locations for those placed underneath the rubber tree plantation, and also at 4.9 m away from the rubber trees, with a light availability of approximately 80%, towards the monocrop. In the distance of 1.5 m, with close to 45% of radiation, the LAI value observed was intermediate (Table 15.1). The same variation pattern was observed with total leaf area, but with a sudden increase in the first rows next to the rubber trees (1.5 and 4.9 m).

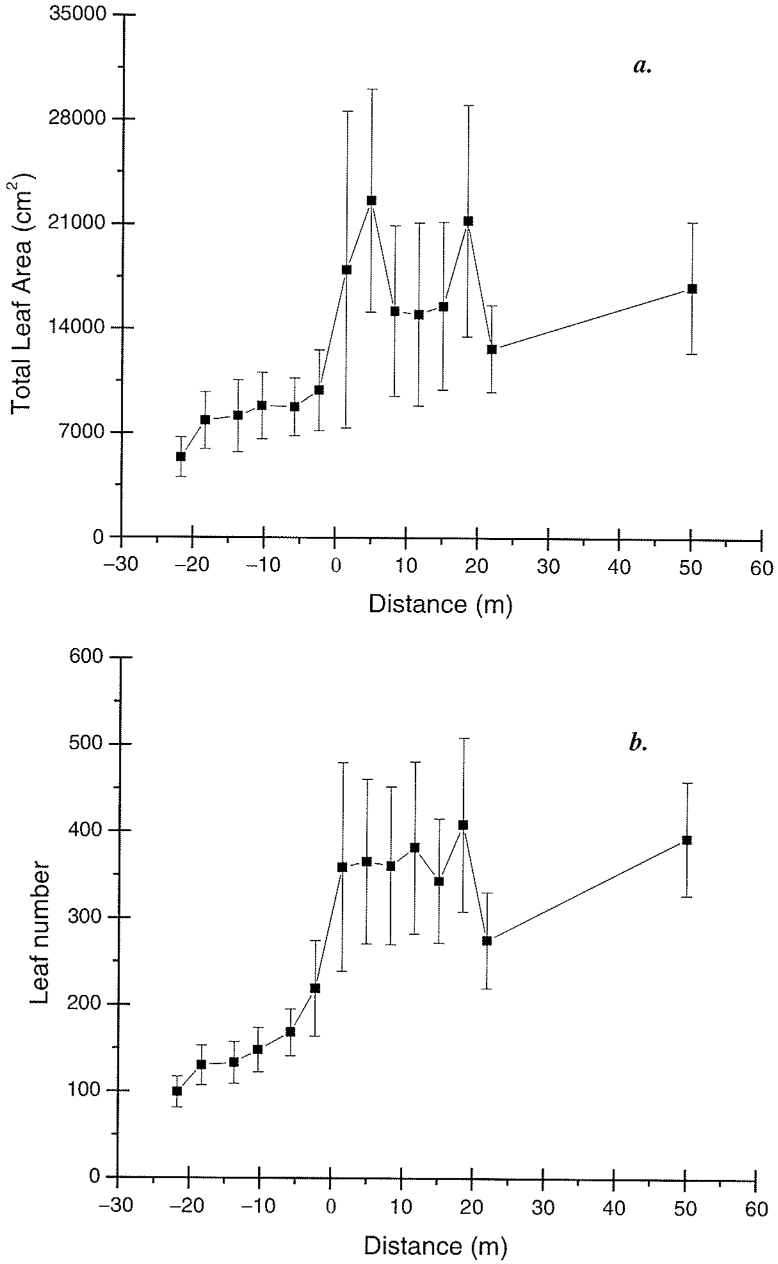

Figure 15.5 (*a*) Total leaf area (cm^2) of coffee plants in respect to the distance from the rubber tree plantation. (*b*) Average number of leaves of coffee plants in relation to the distance from the rubber tree plantation. Negative distances refer to the inside of rubber plantation

Table 15.1 Coffee plant parameter values, genotype Obatã IAC 1669–20 – Mundo Novo, distance from trees, evaluated from the first rubber tree row interfacing coffee plants (distance zero) (negative distance refers to the inside of the rubber tree plantation, and positive to an increase in distance towards the coffee monocrop); **irradiance fraction** (I/I_0), which was the quotient between the irradiance measured value and their respective distances (I) by the values measured above the canopy (I_0); **stem diameters** at 5 cm from ground (mm); **plant height** (cm); **stem height** (cm); **canopy diameter** (cm); **canopy height** (cm) which is the difference between the measurements of tree and stem height; **canopy rounding** or canopy filling ratio, which is the average diameters and the canopy length quotient and indicates the circular shape level; **leaf area index** (m^2m^{-2}); **canopy percentage** (%), which is the canopy height percentage of the tree's height; **canopy opening** (%), which is the percentage of the canopy average diameter divided by tree height; **canopy projection** (%), which is the average canopy diameters over the stem diameter; **canopy volume** (cm^3), which was calculated considering a conic shape; and **leaf density** (cm^2 cm^{-3}), which is the total leaf area and canopy volume quotient

Distance (m)	Irradiance fraction (I/I_0) (%)	Stem diameter (mm)	Plant height (cm)	Stem height (cm)	Canopy diameter (cm)	Canopy height (cm)	Canopy rounding	LAI (m^2 m^{-2})	Canopy (%)	Canopy opening (%)	Canopy projection (%)	Canopy volume (cm^3)	Leaf density ($cm^2.cm^{-3}$)
–21.7	–	11.72	54.50	24.70	60.35	29.80	2.03	1.97	54.41	110.17	5131.03	30716.22	0.21
–18.3	–	11.38	57.25	22.83	74.04	34.42	2.18	1.83	60.20	129.52	6529.24	50111.49	0.16
–13.7	25	12.48	56.95	23.89	72.39	33.07	2.31	2.00	57.74	127.86	5812.54	46453.78	0.20
–10.3	30	13.14	58.18	25.02	75.91	33.16	2.47	1.97	56.48	131.63	5800.47	50858.10	0.20
–5.7	35	14.11	59.04	25.60	76.83	33.44	2.47	1.96	56.28	131.19	5448.60	53600.82	0.19
–2.3	40	15.70	64.17	25.75	81.48	38.42	2.42	1.91	59.15	128.20	5226.27	68418.93	0.17
1.5	45	18.71	70.67	19.60	81.81	51.06	1.63	3.38	72.13	116.23	4419.81	92284.26	0.20
4.9	80	18.22	66.60	20.32	77.49	46.28	1.75	4.84	69.05	116.77	4306.24	77219.10	0.35
8.3	90	18.18	63.33	21.49	73.28	41.84	1.83	3.65	65.50	115.84	4041.10	61851.50	0.28
11.7	95	18.78	64.55	19.35	73.43	45.20	1.64	3.58	69.83	113.60	3934.26	66679.70	0.24
15.1	100	17.68	60.00	21.92	69.05	38.08	1.85	4.18	63.04	115.10	3908.75	51178.49	0.35
18.5	100	19.47	63.81	22.94	73.82	40.88	1.88	4.97	63.41	116.12	3799.66	62501.86	0.39
21.9	100	16.64	53.75	21.58	60.71	32.17	2.10	4.45	59.12	113.69	3659.29	32419.45	0.49
Monocrop	100	18.59	61.16	19.38	71.73	41.78	1.74	4.27	68.23	117.76	3897.39	57430.59	0.31

Leaf density (cm^2 leaf cm^{-3} canopy) was much higher when coffee plants received close to 100% solar radiation, double the value in some extreme cases. Higher leaf density (Table 15.1) and number of leaves (Figure 15.5b) in illuminated plants confirm the short distance between leaves within the canopy, as well as the barrier against high incidence of radiation. On the other hand, coffee plants under more shade (under rubber trees, receiving only about 25% of the total radiation) presented larger leaves, spaced further apart. Among the plants positioned in order to receive more radiation, the average leaf area was of approximately 45 cm^2, while those placed under lower radiation availability presented an average leaf area of 55 cm^2. The SLA increase in the latter was not enough to equal neither the leaf area nor the LAI to those of plants receiving more light, resulting in poor soil coverage and interception of radiation. Such decrease leads to smaller growth and dry matter accumulation.

The results obtained agree with those found by Russell et al. (1989), who affirm that, when the density of leaf area is lower, there is a high probability that a ray of light might cross the canopy without being intercepted. On the other hand, under higher leaf density conditions, the light might be absorbed or dispersed, not reaching the lower canopy layers. Robledo (1979) found that coffee plants growing under full sun form an extern layer of leaves that absorbs around 90% of the radiation, resulting in a smaller percentage being available to the inner layers (close to 5%). Sakamoto and Shaw (1967) observed the same in soybean canopies and Alvin (1977) in cocoa trees. Kumar (1978) reached similar conclusions studying coffee plants in high density situations (over 15,000 plants ha^{-1}).

Other parameters evaluated share the same tendency observed for LAI, with a sharp increase when coffee plants received 45% of the available radiance, which occurred at the first position, when coffee plants were 1.5 m away from the trees. It is possible to observe the existence of two landing values with a transition zone (45% light availability) that suggests coffee plants are very sensitive to further light decrease, which can be considered a turning point.

The data confirms Horn's (1971) results, who states that there is an increase in carbon fixation if the canopy layer increases (LAI). Increases in radiation levels lead to an improvement on light transmission, which results in a bigger LAI. Thus, plants exposed to the sun present leaves in a diffused arrangement, in several layers; while plants under shade conditions present leaves in a uniform layer (Horn, 1971). Low self-shading strongly affects the carbon balance, mainly in environments where radiation is close to the compensation point (Givinish, 1984).

LAI was slightly smaller in the more shaded places, since its calculation considered the canopy projection. It was clearly observed that there was no increase of the area coverture, given by the canopy diameter, with the increase in irradiance and vice versa. Bigger canopy diameters (81.48 and 81.81 cm) were observed closer to the rubber trees – at the distances of –2.3 and 1.5 m.

The canopy opening did not change much in the evaluated positions, suggesting that it is a conservative parameter, despite tendencies to increase under shade (maximum values of 130 under shade against 115 under sun conditions) (Table 15.1). Canopy opening was close to what was estimated by King (1981) and recorded by

Givinish (1986). In spite of a decrease in radiance availability to the coffee plants near the trees' edge, and the fact that there was still enough space between rows, which would allow for bigger canopy openings, the plants were touching each other in the rows, which leads to an increase in height.

The sharp reduction of canopy projection with the distance from the trees' edge was mostly due to an increase in stem diameter (from 11.38 mm in more shaded regions to 19.47 mm) than to differences in canopy diameters (Table 15.1).

Coffee plants presented clear variation in canopy architecture, mainly in the vertical way, as observed in the canopy height, which increased closer to the rubber trees edge. The canopy percentage suggests a higher capacity of the plants to intercept and use the radiance. The same pattern was observed on canopy volume, despite a strong inflexion in intermediate distances. The biggest canopy volume was observed at 1.5 m (92284.26 cm^3). Such results indicate a canopy architecture plasticity of coffee plants under different light availabilities, with several light interception and use patterns.

Because of vertical growth due to neighboring plants and light availability decrease caused by the rubber trees, the lowest branch intersection (given by the stem height) was higher in shaded plants (24.5 cm). A tendency to decrease towards a monocrop (where lowest stem intersection was about 19 cm) was observed. Bigger stem height contributes to improve canopy opening and leads to an oblong shape (2.5) of the coffee canopies under shade, while those under full sun (monocrop) presented a tendency towards spherical canopies (1.5) (Table 15.1).

Loss of basal branches in coffee plants is very often related to them being planted in high density or under overshaded conditions. Coffee plants do not replace plagiotropic branches (yield branches) even when there is an increase in irradiance, deeming the plant permanently damaged, representing a substantial yield loss.

Monsi and Saeki (1953) demonstrated that the extinction coefficient (k) tends to be higher in species with width and horizontally distributed leaves ($k \approx 0.6$ to 0.9) than in those with smaller and vertical leaves s ($k \approx 0.3$ to 0.5). It is expected that under shade conditions the light extinction coefficient would be higher than those found in light conditions, but such fact needs to be studied further. Robledo (1979) observed k values of around 0.41 ± 0.15 inside the coffee canopy. And that radiation extinction occurred in exponential way at noon, when coffee plants presented lower albedo. These facts indicate that coffee is highly efficient on energy absorption.

Coffee plants present several characteristics that allow a strong attenuation of the radiation available. Cannel (1976) observed that coffee plants use a large part of their dry matter to increase the leaf area. Coffee plants present high light transmission inside the canopy, upper branches in small angles, leaves placed in long vertical distances, and conical shape that prevent self shading.

Besides LAI, another important geometric canopy characteristic that determines the net carbon assimilation is its mechanic efficiency, the energy fraction allocated to the leaves in relation to non-productive organs. Canopies are important to harvest and convert energy, and are also important to competition (Givinish, 1988). This author considers that leaf maintenance cost has to include the compensation point, as well as leaf, branches and roots construction, that increase the ecological compensation point. In this manner, the maintenance cost and the plant height are important to determine its survival under shade condition. Givnish (1988) re-analyzed the data of Björkman et al. (1972) and suggested to express photosynthesis and respiration as a function of leaf mass or protein content in a way to incorporate the leaf construction costs and to asses its adaptation to light level, which becomes more apparent than if expressed by leaf area. By doing this, the higher rates of return at low irradiances of leaves adapted to those conditions become evident. This way, it is not surprising that canopies under direct sun, with leaves exposed to many different light environments and adapted to them, have each individual leaf working at its maximum. Thus, due to larger photosynthetic tissue than those present on shaded plants, the sun plants – as in this case with double LAI – showed great gross photosynthesis and total dry matter accumulation.

The results showed different coffee plants behavior in respect to radiation interception and attenuation, and allocation of photosynthetic compounds under several environments. All the parameters evaluated presented high linear statistical significance (**) along with the transect showing a clear tendency.

Figure 15.6 shows the total dry matter produced versus the available solar radiation. A good development can be observed under 45% of the total light available, at 1.5 m from the rubber trees. The results obtained differ from those widely reported in respect to their direct correlation (Pereira, 2002; Righi, 2000; Beer et al. 1998; Confalone et al. 1997; Russell et al. 1989). Such fact is probably due to previous studies being carried out with plants that had fast growth and canopy closure, while, on this study, the canopy closure was partial. Thus, the available radiation interception was very different in the evaluated positions, and a good correlation was not found. Another alternative is to agree with Šesták (1981), considering that the relation between dry matter and radiation may change along the plant's life, as the coffee plants in this study were still in development.

Another alternative explanation to the abrupt decrease in dry matter accumulation, and its relation with the available radiance to coffee plants at −5.7 m from the trees (around 35% of radiation), may be the active photosynthetic radiation (PAR) as these coffee plants were completely underneath the rubber trees, which act as a radiance filter (Russell et al. 1989; Larcher, 1995). Nevertheless, more than such decrease, it is important to emphasize the likely increase in radiance interception efficiency and its conversion by plants at 1.5 m from trees (with around 45% of the irradiance).

Russell et al. (1989) consider that the linear growth response to PAR absorbed was expected, since the canopy was not exposed to saturating radiances during most of its growth season. The point is: did plants, at 1.5 m from the trees, reach the saturation of their canopy with only 45% of the available radiation? Such radiation values would be close to the saturation point of isolated leaves (close to ⅓; of the irradiance in a clear summer day), far from those that normally would saturate a canopy. In the case of this hypothesis being right, if that data was not considered, the correlation would be much higher and a better adjustment would change r^2 from 0.41 to 0.74.

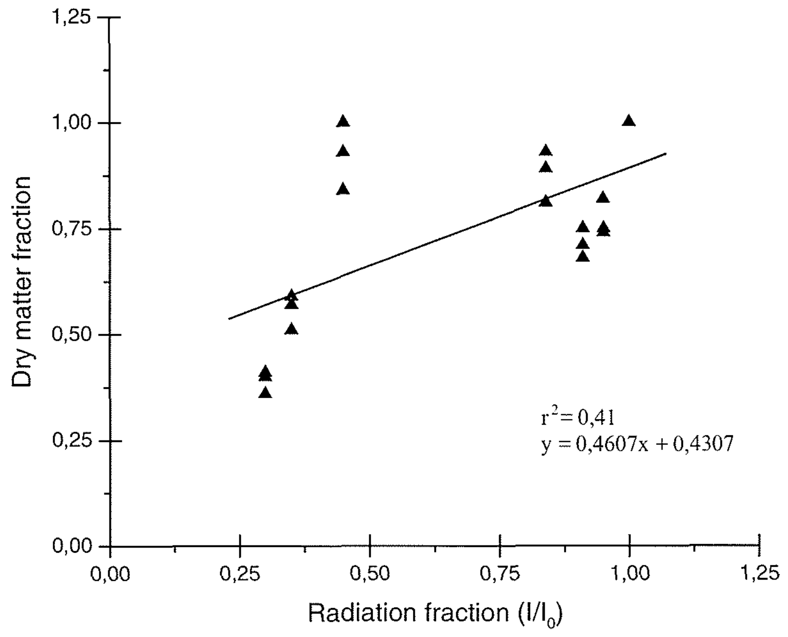

Figure 15.6 Above ground dry matter fraction (Dmf) as a function of available radiation fraction ($Rf=I/I_0$)

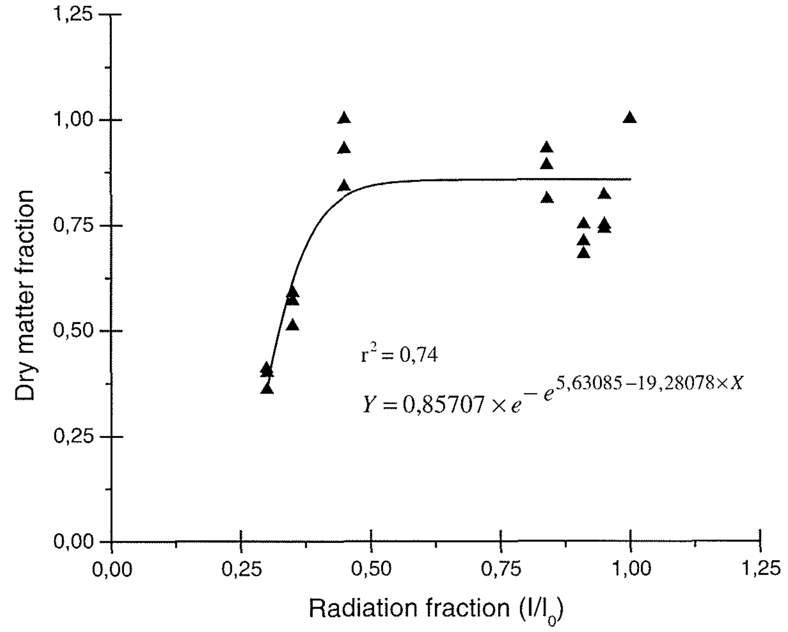

Figure 15.7 Adjustment of the Gompertz model to the dry matter fraction (Dmf) of the coffee plants as a function of the available radiation fraction ($Rf = I/I_0$)

The Gompertz model presented a great adjustment to the collected data, when r^2 was 0.74 (Figure 15.7). Through this model it is clearly observed that coffee plants reach the saturation point at 45% of the available irradiance. It is possible to observe a linear correlation until reaching the saturation point as Russell et al. (1989) demonstrated. At 45% of the radiation, dry matter values were at the same landing.

Final Considerations

There still is a large the number of papers on radiation influence that do not bring any mention to its measurement, limiting themselves to determine whether the treatment was shaded or not. The authors would like to highlight the importance of solar radiation measurement, since it is the main energy source driving all the processes and has a number of implications over the production system.

The use of AFS by coffee producers can result in the development of this crop in regions previously declared improper due mainly to stress caused by inappropriate air temperatures. As studies of irradiance carry an inevitable thermal component (infra red thermal), it is common sense among researchers that coffee plants do not tolerate high radiation levels. This is not true, as we can see from many coffee plantations near the equatorial zone, e.g. in Brazil, Ethiopia, and Kenya, for as far as air temperature allows it. Future works on the play and exchange process of temperature seem to be very promising for the future development of AFS and coffee crop.

Conclusion

The mathematic model, proposed by Goudriaan (1977) and adapted by Bernardes et al. (1998), properly describes the radiation available to intercalary plants. It can be an important tool to AFS planning and analysis.

Coffee plants presented good plasticity with changes in SLA, LAI, leaf density, canopy geometry, and radiation interception and use.

The crop did not present a good linear correlation between available radiance and dry matter accumulation, probably due to canopy saturation at 45% of the available radiation. The best adjustment was obtained in the Gompertz model.

No decrease in dry matter accumulation was observed when the irradiance was at 45% of the availability. Further reductions on light availability caused abrupt decreases in dry matter accumulation, and changes in the adaptation to such conditions.

Due to its high adaptation capacity to significant decreases on radiation availability, coffee cultivation in AFS presents good perspectives.

Acknowledgments Special thanks to the State Agency for Research of São Paulo/Brazil – FAPESP – for the support and to Professor Dr. José Dias Costa for his unconditional help and ideas.

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Chapter 16

Modeling Green Manure Additions in Alley-Cropping Systems: Linking Soil Community Dynamics and Nitrogen Mineralization

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Introduction

The use of biomass in the form of litter, prunings, or roots as sources of nutrients for crops in alley-cropping systems has proven helpful in enhancing nitrogen availability for crops (Nair et al., 1997). Important considerations in managing alley-cropping systems are the amount and rate of N released that can benefit the crop in the alleys between the hedges. Understanding the short-term mineralization patterns of organic materials is a useful tool not only to assess but also to improve the suitability of hedgerow species (Isaac et al., 2000). Numerous studies in controlled and field conditions have successfully addressed the short-term decomposition and mineralization patterns of different species in relation to the initial chemical quality of the residues in order to make practical management suggestions. However, initial chemical quality of substrates alone is sometimes not sufficient to explain short-term mineralization patterns. This is not surprising given the multiplicity of factors influencing decomposition and mineralization, including biochemical characteristics and soil biota composition and dynamics (Heal et al., 1997).

Soil biota plays an important role in regulating nutrient mineralization. Interactions among soil community members regulate the availability of the nutrients necessary for plant growth (Wardle, 2002). Direct trophic interactions are responsible for a great fraction of nutrient release. For example, (de Ruiter et al. 1994) estimated that protozoa feeding on bacteria were responsible for up to 95% of the total N released into the soil in two arable farming systems. Agricultural practices such as residue addition can affect population size and dynamics of organisms in soil food webs (Wardle et al., 1999) in turn affecting nutrient cycling processes. Understanding how the addition of green manure influences the soil community and how this change in turn influences N mineralization patterns might help in managing soil biota and plant material selection and application to optimize nutrient utilization.

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

A potentially useful tool to study these interactions is the use of organism-oriented models. Organism-oriented mathematical models that track the flows of nutrients through groups of organisms have high explanatory value and can integrate the effects of management in the description of mineralization (Paustian, 1994). A relatively successful approach is the soil food web model by Hunt et al. (1987). Carbon and nitrogen mineralization rates can be satisfactorily derived from trophic interactions simulated through these mechanisms (de Ruiter et al., 1994). Soil food web models have proven useful for evaluating the relative contribution of functionally defined groups and particular trophic interactions to carbon and nitrogen cycling (Berg et al., 2001).

The purposes of this study are: to asses the impact of green manure addition on the soil community in an alley-cropping system; to assess the performance of a soil food web model (Hunt et al., 1987) in simulating nitrogen mineralization rates from plant substrates, and to test the hypothesis that take into account the soil biota structure and dynamics – in addition to biochemical quality – is important for explaining short-term mineralization patterns from green manures and other plant residues in alley-cropping systems. For this, nitrogen release from three plant materials was measured over a growing season. Also the dynamics of the soil community were monitored in bare soil and after the addition of prunings of the leguminous tree *Albizia julibrissin* Durazz. These results were used to initialize and test the model. Simulations were then conducted to study how the influence of residue addition on the soil biota affects nitrogen mineralization.

Materials and Methods

Study Site

This study was conducted in the Piedmont region of Georgia, USA (33°57′N latitude 83°19′W longitude). The climate is humid subtropical with an annual average temperature of 18 °C. Precipitation is uniform throughout the year and averages 1200 mm. The soil is an Ultisol (kaolinitic, thermic, typic, hapludults) with a sandy loam texture. Soils have a pH in water of 5.8 (1:1). The site is located on a previously abandoned conventional monoculture farmland. In 1990, hedgerows of Albizia (*Albizia julibrissin* Durazz) were planted. Since then, cultivation of sorghum, wheat, and corn in the alleys between the hedgerows has been alternated with fallow periods.

Nitrogen Mineralization

Nitrogen release was measured in the field under *A. julibrissin* prunings (from here on referred as albizia) addition and in bare soil. Prunings consisted of a weighted mixture of leaves and woody twigs. For model validation purposes, release from prunings of another hedgerow species (*Alnus serrulata* (Ait) Willd) and of the roots of albizia were also measured. Roots of albizia were chosen as a substrate to explore their mineralization rate because in some alley-cropping systems roots are mechanically severed to prevent competition with crop species, and the severed roots subsequently decompose. Release of NO_3^- and NH_4^+ from substrates was determined by incubation of undisturbed soil cores containing anion and cation exchange resins at their bottoms (Kolberg et al., 1997). Incubation cores were prepared by driving plastic sleeves (5 cm diameter × 8 cm long) into the soil and then withdrawing them with the soil inside. The bottom 1 cm of soil was removed and a nylon bag filled with resin was put in its place. The entire assembly was returned to the original hole. The resin used consisted of equal amounts (15 g) of a Na-saturated cation and Cl-saturated anion exchange resins (Sybron Ionac C-250 and ASB-1P, Sybron Chemicals, Birmingham, NJ).

Substrates were oven dried (70 °C – 48 h) and 3.5 g of albizia (1.9 kg m^{-2}), 2.5 g of albizia roots (1.4 kg m^{-2}), and 2.5 g (1.4 kg m^{-2}) of alder were placed on the surface of each core. The amounts were chosen to resemble yields from prunings and stocks in the soil. A plot parallel to an albizia hedgerow was chosen to be the experimental plot for in situ incubations. Naturally occurring litter and live plants were removed from the soil and no plants were allowed to grow within the plot. To obtain baseline levels of NO_3^- and NH_4^+, ten randomly distributed composite samples were collected upon initiation of the study.

Cores were distributed in the plot and treatments were randomly assigned to the cores. Each core was considered to be a replicate. Resin bags were incubated for a maximum of 6–7 weeks after which they were replaced with new bags. Six soil cores per treatment were collected after 18, 48, 84, 115, 129, and 148 days. Complete assemblies were removed from the field, transported to the lab and refrigerated for up to a week until processed. Resin bags were washed with deionized water to remove soil and debris and then extracted for NO_3^- and NH_4^+ by shaking intact bags in 60 ml of 2 M KCl for 1 h. Each soil core was subsampled to measure gravimetric water content at 70 °C for 48 h, and NO_3^- and NH_4^+ concentrations. An extraction was made from 4 g of fresh soil by shaking in 20 ml of 2 M KCl for 1 h. Resin and soil extracts were analyzed using an Alpkem Continous Flow Analyzer. Nitrate and NH_4^+concentrations were corrected for soil moisture content and converted to milligram per gram of dry soil. Concentrations of mineral N were calculated for each core using the combined amounts of NO_3^- and NH_4^+ in both soils and resins. The concentration of total mineral N in all soil samples was converted to milligram per square meter using the averaged value of bulk density. Net mineralization for each incubation period was calculated as the difference between final and initial N concentrations.

Initial plant material was processed for total C and N using the micro-Dumas combustion assay and Neutral Detergent Fiber and Acid Detergent Fiber. Lignin, cellulose, and hemicellulose percentages were calculated. At the end of the incubation period, final C/N ratio was determined.

ANOVAs were used for comparisons between dates and treatments. Simple linear regressions were performed between percentage of remaining C and N and quality parameters. Unless otherwise stated all significant differences are reported at the $P \leq 0.05$ level.

Effect of Addition of Green Manure on the Soil Community

The effect of the addition of Albizia prunings on the soil community was assessed in the field. Microbial biomass, Whole-Soil Fatty Acid profiles, biomass of protozoa, nematodes, and microarthropods were monitored from May to September 2002 after the addition of Albizia prunings and in bare soil. Treatments were randomly assigned to four plots. Pruning of albizia trees was carried out in late May and a mulch bed was placed in two of the plots. Sampling for biomass measurements began upon addition on 20 May, and was repeated on 27 June, 22 August, and 22 September. Eight 8-cm depth soil samples per treatment were collected on each date. Gravimetric moisture was determined for all samples (70 °C – 48 h). Abundances were calculated on a per-dry-weight basis and then converted to mg C m^{-2} using an averaged value of bulk density for the study area (1.13 g cm^{-3}).

Microbial carbon was determined using the Chloroform Fumigation Extraction method (CFE) (Vance et al., 1987). Four 20-g samples of fresh soils were fumigated with chloroform for 24 h. Samples were extracted by shaking for 1 h with 80 ml of 0.5 M K_2SO_4. Extracts were filtered and analyzed for Total Organic Carbon (TOC) (Shimadzu TOC-5000A). Microbial C was calculated using $K_c = 0.42$.

Protozoa were processed with the most probable number method using 10-fold dilutions of 10-g subsamples and *Escherichia coli* as a food source. Samples were incubated at 25 °C for 3 days after which individual wells were inspected and individuals enumerated. Biomass C was estimated from the cell numbers using an average volume of 300 μm^3 for ciliates and 50 μm^3 for flagellates (Berg et al., 2001). Specific density was set as one, dry mass as 20% of fresh mass and C content as 50%. Protozoa counts were only carried out for June 26 and August 28 samples. Approximately 6 g (fresh weight) of soil were extracted for nematodes with the Baermann Funnel method for 72 h. Nematodes collected were preserved in 5% formaldehyde and later enumerated. Biomass C was estimated from the number of individuals using a mean individual biomass of 0.034625 µg dry weight (Sohlenius and Sandor, 1987) and the conversion factor of 50% for C content. Microarthropods were extracted (4 days) on Tullgren-type extractors (Crossley and Blair, 1991). Number of individuals was converted to biomass C using average values for each major taxonomic group (Beare et al. 1992).

Whole-soil Fatty Acid Methyl Ester (FAME) analysis allows characterizing whole microbial communities in order to explain their relative differences and similarities. FAME profiles were obtained by the ester-linked method (Schutter and Dick, 2002). Duplicate analytical replicates were used for each of four samples per treatment. First, lipids were saponified by adding 15 ml of methanol-KOH (0.2 N) to 3 g air-dried soil samples and heating for 1 h at 37 °C with periodic vortexing. After neutralizing with 1 N acetic acid, 10 ml of hexane were added and the mixture vortexed and centrifuged at 480 × *g* for 20 min. The top phase was transferred by pipette to disposable test tubes that were placed in a 40 °C water bath. Extracts were evaporated under a gentle stream of N_2. FAMEs were resuspended in 0.5 ml of 1:1 hexane: methyl-tert-butyl ether and transferred to a GC vial for analysis by Hewlett-Packard 5890 gas chromatograph (Palo Alto, CA). FAMEs were identified using the standard Eukary chromatographic program and peak naming table as supplied by MIDI (Microbial, ID, Inc. Newark, DE). In order to examine the effect of date and treatment on community structure, FAMEs, as percentages of total FAMEs within a sample, were divided into chemical categories (Buyer et al., 2002) and analyzed using Principal Component Analysis (PCA). With PCA, multiple original variables (fatty acid percentages) are reduced to a smaller number of uncorrelated variables called principal components that explain the overall variability. The first principal component accounts for as much of the variability as possible and succeeding principal components account for the remaining variability. Fatty acid biomarkers (as the areas of their peaks in the FAMEs profiles) were used as relative measures for bacteria and fungi as in Mummey et al. (2002). Biomarker fatty acids and biomass C of organisms were analyzed using repeated measures ANOVA to test for the effect of treatment and sampling date. Tukey-Kramer HSD tests were used when significant differences were found. Student *t* tests were performed for comparison between treatments by date. All biomass data were log transformed prior to statistical analysis. Significant differences are reported at the $P \leq 0.05$ level.

Effect of the Change in Soil Community on Nitrogen Mineralization

To study the influence of soil community changes after green manure addition, the soil community food web model developed by Hunt et al. (1987) was adapted to simulate the dynamics of nitrogen mineralization from green manure. The model simulates mineralization from transfers of C among soil functional groups. In this study we use the model by applying it to the observed population sizes of the groups of organisms and C/N ratio of substrates. Physiological parameters such as assimilation rated and C/N ratios of organisms used for simulation were taken from Hunt et al. (1987). The model was calibrated using observed mineralization rates under bare soil. Carbon flows are derived from feeding rates, which are in turn split into an excretion rate, a biomass production rate and a mineralization rate. Observed soil populations biomass changes through the growing season are incorporated into the model as inputs by adding the estimated rate of change in biomass to the rate of material loss due to natural death and predation (de Ruiter et al., 1993). Rate of change in biomass was estimating by dividing the difference between measurements by the number of days between measurements. Feeding rates are calculated assuming that the biomass production rate of a group balances the rate at which material is being lost through natural death and predation. Feeding rate of a group on a prey or on a substrate is calculated as follows:

$$F = (Dnat \times B + P + \Delta B)/eass \times eprod$$

where *F*: feeding rate; *Dnat*: natural death rate; B: biomass of functional group; *P*: predation rate; ΔB: observed change in biomass; *eass*: assimilation efficiency and *eprod*: production efficiency. Nitrogen flows occur in parallel and in proportion to C flows through the use of the C/N ratios of organisms and organic matter.

Nitrogen mineralization rate is calculated as:

$$\mathrm{Nmin} = \mathrm{eass} \times ((1/\mathrm{CNprey}) - (\mathrm{eprod}/\mathrm{CNpred})) \times \mathrm{F}$$

where *Nmin*: mineral nitrogen released per trophic transfer; *eass*: assimilation efficiency of the consumer; *CNprey*: carbon to nitrogen ratio of the prey or substrate; *eprod*: production efficiency of the consumer; *C/Npred*: carbon to nitrogen ratio of the consumer; *F*: feeding rate of consumer on prey. Soil temperature was measured daily and death rates were related to temperature using a $Q_{10} = 3$ (Andren et al., 1990). The model was applied to simulate daily N mineralization during one growing season (150 days). The soil community was modeled as a simplified food web composed of five functional groups: bacteria, fungi, protozoa, nematodes, and microarthropods. The substrate to be mineralized was divided into labile material, cellulosic/hemicellulosic material and lignin. All forms are processed by bacteria and fungi. The specific groups and trophic interactions considered are shown in Figure 16.1. Total consumption demand by one group is split into the three substrates by adjusting the calibrated decomposition rate constants (k) of these substrates (Schomberg and Cabrera, 2001) to reflect bacteria and fungi differences in substrate utilization. The C/N ratio of substrates used was the weighed average of observed initial and final C/N. When no residue was added, a ratio of 25 was assumed for soil organic matter. To evaluate the performance of the model, it was applied to observed population sizes of the groups of organisms and the observed C/N ratios of albizia prunings, albizia roots, and alder. Simulated and measured values were then compared. Two types of general population dynamics were used for simulations: one for when residue was applied and one for when no residue was added.

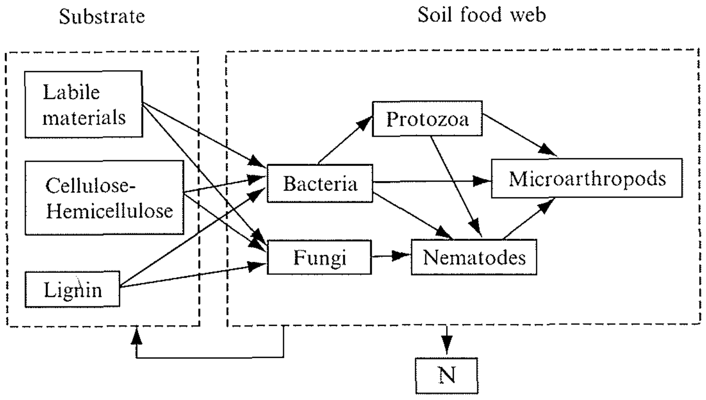


Figure 16.1 Trophic interactions described in the soil food web model used for an alley cropping system

Results

Chemical Composition of Substrates and N Dynamics

Initial chemical composition of substrates is summarized in Table 16.1. Albizia prunings had the lowest C/N ratio and Alder had the highest. Albizia prunings and albizia roots had similar N contents and C/N ratios but differed considerably in their lignin contents. Lignin content of roots was twice as high as prunings of albizia. Roots had the highest lignin concentrations (22%). Alder contains relatively low lignin and cellulosic material but its N content is lower than the other substrates. Although alder had a higher C/N ratio that albizia at the beginning of the incubation, it was the lowest at the end followed by albizia roots Table 16.2.

Figure 16.2 presents field concentrations of mineral nitrogen (NO_3^- and NH_4^+) in soil. Initial mineral nitrogen concentration averaged 10,000 mg m^{-2}. At the end of the season, a net average increase of ca. 11,000 mg m^{-2} was observed for both the albizia and albizia roots treatments. No net immobilization was observed in soils amended with albizia. Albizia roots, alder, and bare soil showed alternating periods of net immobilization and net mineralization. The alder treatment consistently rendered the lowest N concentrations and no significant change in concentration was observed at the end of the season.

Table 16.1 Initial quality parameters of *Albizia julibrissin* prunings, *A. julibrissin* roots, and *Alnus serrulata* prunings and final C/N ratio after field incubations in an alley-cropping system in Georgia, USA

Parameters	Albizia prunings	Albizia roots	Alder prunings
Initial %C	45.01	41.74	46.3
Initial %N	2.49	2.09	1.92
Initial C/N	18.08	19.94	24.13
Final C/N	17.01	14.86	13.27
% Ligning	10.96	21.77	12.52
% Cellulose–Hemicellulose	43.34	43.62	33.34
Lignin/N	4.4	10.4	6.5

Table 16.2 Repeated measures analysis of biomass of soil organisms over time under bare soil and soil amended with albizia prunnings in an alley-cropping system in Georgia, USA. *P* values are showed for significant effects. N.S: Not significant

	Microbial biomass	Nematodes	Microarthropods
Time	$P < 0.0001$	N.S.	$P = 0.0296$
Treatment	N.S.	N.S.	N.S.
Time × Treatment	N.S.	$P = 0.0103$	N.S.

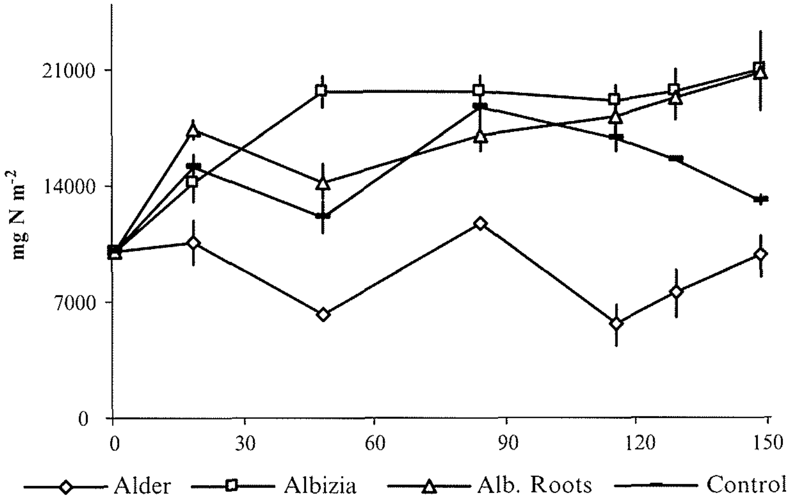


Figure 16.2 Soil concentrations of mineral nitrogen ($NO_3^- + NH_4^+$) (means +/– SE) after addition of *Albizia julibrissin* prunings, *A. julibrissin* roots, and *Alnus serrulata* prunings and in bare soil

Albizia prunings showed the highest average mineralization rate (55 mg N m^{-2} day^{-1}, SE=7) closely followed by albizia roots (50 mg N m^{-2} day^{-1}, SE=27). Mineralization rate in bare soil was 23 mg N m^{-2} day^{-1}, SE=2 while the rate of alder was found to be close to zero and negative (–1.49 mg N m^{-2} day^{-1}, SE=10).

Effects of Addition of Albizia Prunings on the Soil Community

Microbial Community

PCA of FAMEs demonstrated differences in the microbial communities associated with treatment and time. The first two principal components accounted for 65% of the total variance (Figure 16.3). The ordination shows separation by treatment along PC 1 (34% of variance) and no evident separation by date indicating that the presence of green manure rather than time was the strongest influence on the microbial community structure. Overall, fungal biomarkers peak areas were significantly greater in the albizia treatment (Figure 16.4). Bacterial biomarkers were greater in the albizia treatment as well, but this difference was not significant. The ratios of bacterial to fungal biomarkers were consistently and significantly lower in the albizia treatment for all dates. Mean bacterial to fungal biomarkers ratios were 5.9 and 3.6 for the control and albizia treatments respectively.

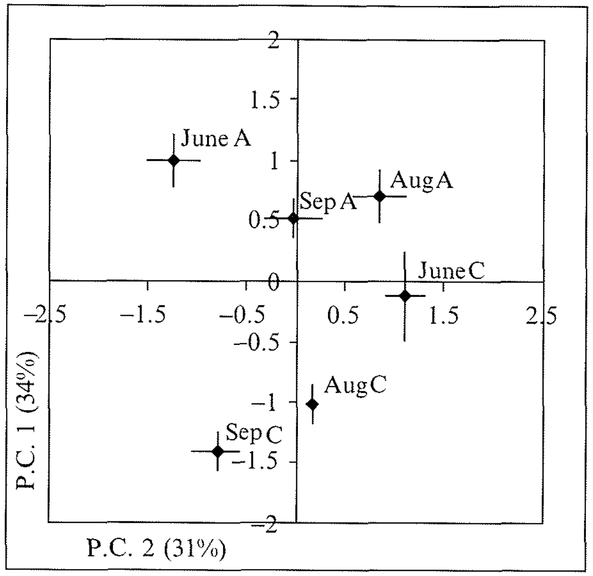
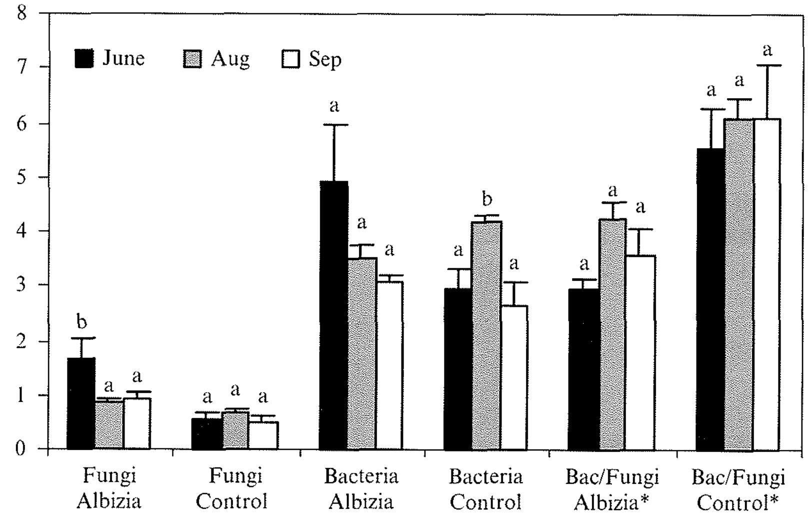


Figure 16.3 Principal Component Analysis of whole soil fatty acids extracted from soils amended with *Albizia julibrissin* prunings and from bare soils. Plot shows the separation of the treatments (A, Albizia and C, Control) using grouped FAMES. Bars indicate the standard error of four replicates. Community positions on PC1 and PC2 are averaged across treatments and dates



*Dimensionless ratio

Figure 16.4 Average peak areas of fatty acid bacterial and fungal biomarkers and their ratios over the growing season in bare soil and in soils amended with *Albizia julibrissin* green manure (means +/– SE). Different letters indicate significant differences between dates

Biomass of Soil Groups

The amounts of biomass C in the various functional groups on the four sampling dates are presented in Figure 16.5. Table 16.1 shows the results of the repeated measures ANOVA for microbial biomass, nematodes, and microarthropod biomass. Soil microbial biomass (Figure 16.5a) ranged from 7000 in May to 30,000 mg C m^{-2} in August. A significant effect of time was observed. No overall significant effect of albizia addition was observed, but microbial biomass was significantly higher under albizia in August. Protozoa biomass ranged from 15 to 85 mg C m^{-2} (Figure 16.5b) and on average constituted 0.1% (bare soil) and 0.5% (albizia) of the total biomass. Under albizia addition, the population increased by a ninefold between June and August while it remained rather stable under bare soil.

On average microarthropods represented 0.1% (control) and 0.15% (albizia) of the total soil biomass. Values ranged from 10 to 40 mg C m^{-2}(Figure 16.5c). A significant effect of time was observed. The highest biomass values for the albizia and control treatment occurred in September and August respectively. No significant overall effect of treatment was observed. However, microarthropod biomass was significantly higher under albizia in June and September.

On average nematodes constituted 0.05% (control) and 0.1% (albizia) of the total soil biomass. No overall effect of time was observed. A significant Time x Treatment interaction was observed. At the beginning of the season nematodes' biomass C was ca. 5 mg C m^{-2} under both treatments (Figure 16.5d). It then significantly increased to 18 mg C m^{-2} as the season progressed for the albizia treatment but remained low and stable in bare soil. No overall significant effect of treatment was observed but late in the season, nematodes' biomass was significantly higher when residue was added than in the absence of residue.

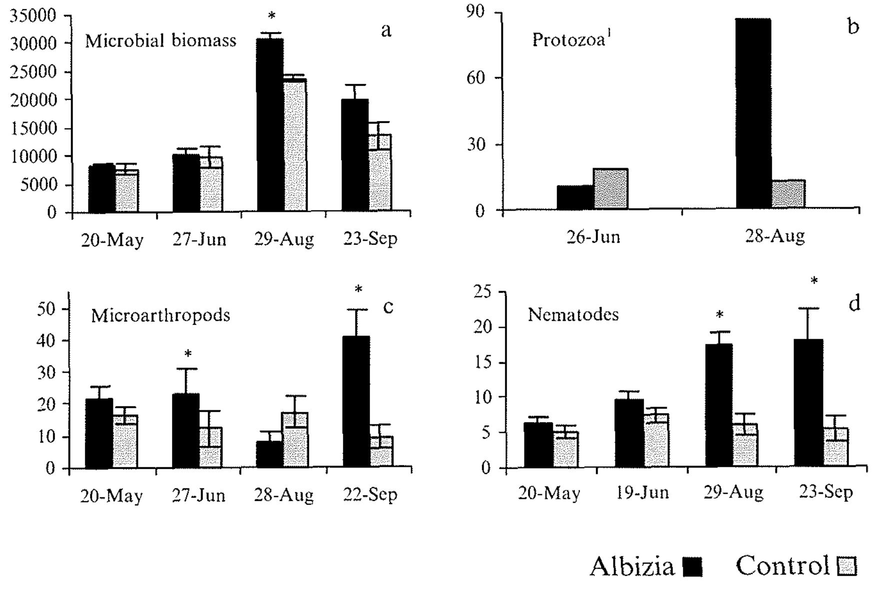


Figure 16.5 Biomass C (means +/– SE) of soil organisms throughout the growing season in soils amended with *Albizia julibrissin* prunings and in bare soil. * Significant difference $p<0.05$. ¹no statistical analysis performed

Soil Food Web Model Performance

The model simulated fairly well albizia's average mineralization and average mineralization in bare soil (Figure 16.6). Average mineralization rate of albizia roots was over-estimated by a 50%. For alder, while the observed net mineralization is close to zero, the model produced an over estimated value similar to albizia roots'. Observed and measured concentrations of nitrogen in soil throughout the growing season are showed in Figure 16.7. Although the model was not able to simulate the periods of immobilization in the albizia roots treatment, the simulated general patterns and final concentrations are reasonably close to the observations for albizia prunings, albizia roots, and bare soil. The concentrations of nitrogen in soil under alder are greatly over estimated by the model.

Effects of Change in the Soil Community on Mineralization

The food web model was used to test the hypothesis that the change in soil community brought about by the addition of green manure influences N release patterns. For this, a simulation of albizia prunings mineralization incorporating the observed changes in soil community was run and then compared to a scenario where no change in the soil community was included (i.e. soil community observed in bare soil). Both simulations were compared to the observed nitrogen concentrations in soil (Figure 16.8). Nitrogen concentrations in soil obtained with simulations not taking

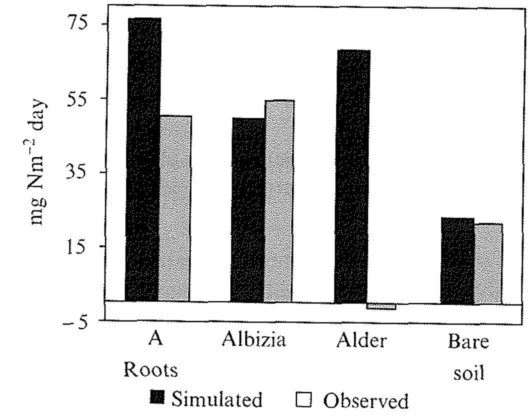


Figure 16.6 Observed and simulated nitrogen mineralization rates after addition of *Albizia julibrissin* prunings, *A. julibrissin* roots, and *Alnus serrulata* prunings and in bare soil

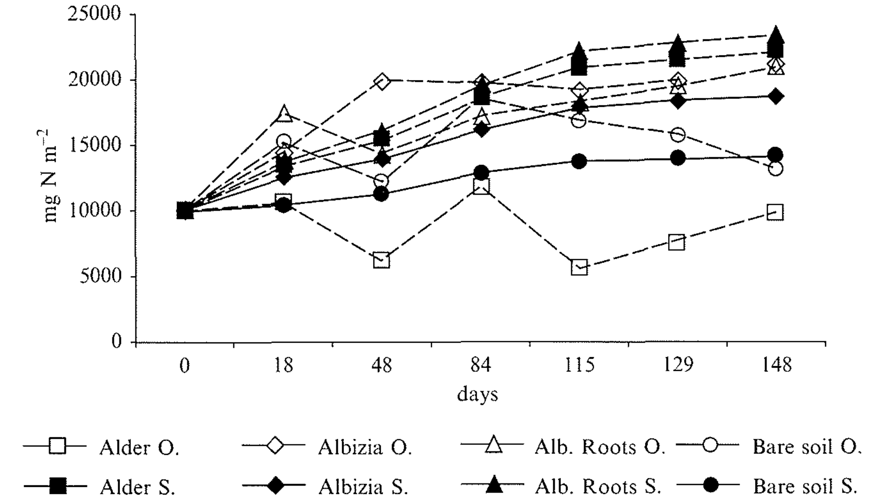


Figure 16.7 Observed (O) and simulated (S) soil nitrogen concentrations after addition of *Albizia julibrissin* prunings, *A. julibrissin* roots, and *Alnus serrulata* prunings and in bare soil

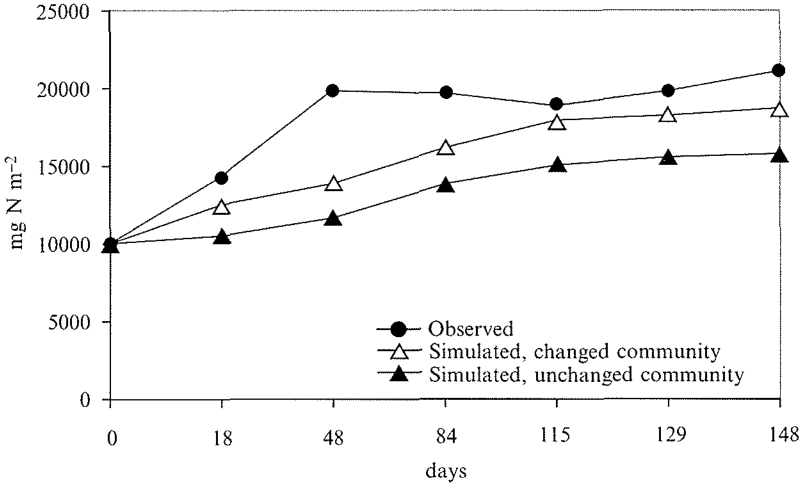


Figure 16.8 Observed soil nitrogen concentrations in an alley cropping system after addition of *Albizia julibrissin* prunings and simulated concentrations obtained with and without including soil community responses to the amendment

into account the changes in the soil community underestimated concentrations by 27%. Incorporating the changes in soil community caused by pruning addition considerably improved the model's ability to predict the concentrations of N in soil. The model still underestimated nitrogen content but only by a 14%.

Discussion and Conclusions

Effects of Addition of Albizia Prunings on the Soil Community

Microbial Community

PCA of fatty acids indicated that the surface application of prunings has a stronger influence in changing the soil microbial community structure than seasonal environmental changes. Microbial groups' biomarkers dynamics supported this observation. Microbial biomass values indicated larger microbial populations at the end of the season when prunings were added, which is very likely attributable to a response to higher substrate availability by detritivores. The comparison of the dynamics of bacteria and fungi biomarkers under plus and minus pruning treatments indicated that the presence of prunings increased the relative proportion of fungi in soil. A greater response of fungi than bacteria is consistent with the conclusion of Wardle (2002) that fungi in soil appear to be regulated chiefly by resources. Seiter et al. (1999) also found larger soil fungal populations associated with green manure inputs in an alley-cropping system.

Fauna

Although no significant overall effect of treatment was observed for the biomass of faunal groups, biomass sizes of protozoa, microarthropods, and nematodes were significantly higher under albizia than in bare soil at the end of the season. Larger microfaunal populations in the presence of added surface residue are commonly observed (Forge et al., 2003). Larger populations can be attributed to greater availability of organic materials and subsequently prey populations (bacteria and fungi) observed in this study. The difference between treatments became higher as temperature and moisture increased in the second half of the study period. These two factors were not monitored separately for each treatment, however, mulched soils present smaller variability and tend to be cooler and retain humidity better (Mathews et al., 2002). Greater relative increases in biomass amounts of all groups under albizia during the late season suggest an enhancing effect of the relatively more favorable microclimatic conditions on organisms' abundances.

As a percentage of total community biomass, faunal groups were between 50% and 100% higher in the albizia treatment, which indicates an influence of the prunings addition on the importance of fauna in the whole community. Zwart et al. (1994) found larger faunal percentages in conjunction with greater fungal populations in an integrated farming system involving addition of organic mulches in comparison to a conventional system.

Model Performance

The approach to soil food web modeling by Hunt et al. (1987) has been satisfactorily used to derive carbon and nitrogen mineralization dynamics from trophic interactions among members of the soil community (e.g. de Ruiter et al. 1994). More recently, Berg et al. (2001) used it to study N mineralization from organic matter in several stages of degradation. Here, we assessed the ability of the model to study mineralization from plant residues by running simulations for residues with different C/N ratios. The model was able to produce mineralization rates for albizia and bare soil that were close to the observed ones. Simulated concentrations of nitrogen for albizia roots were higher than observed. In the case of alder mineralization rates and soil nitrogen concentrations were greatly overestimated. The discrepancies in the case of alder could be due at least in part to the fixed C/N ratio of organisms and substrates in the model, which resulted in no net immobilization by either bacteria or fungi. In the field, a substantial alternation of net mineralization and immobilization periods was observed under alder, which could have been reflecting changes in substrate quality, changes in detritivores populations demand for nitrogen over the growing season or most likely, a combination of both. Changes in population's demand due to shifts in populations' growth or variation of their death rate are accounted for in the model, but change in substrate quality over the season was not described.

The over-estimation of albizia roots and alder mineralization rates might also be related to the fact that quality was represented in the model solely by the average observed C/N ratio of the substrates over the growing season. The examination of initial quality parameters suggested that lignin content of roots could be associated with their lower mineralization rate, which, based on its nitrogen content and ratio, could not be predicted. Since the model is driven only by one aspect of quality (C/N ratio), we obtained an over-estimation, because the C/N of roots is rather low. Another factor that could explain the discrepancy between simulated and observed values for alder and albizia roots is the fact that soil populations were only monitored after the addition of albizia and different residues could have prompted differences in community assemblages (Forge et al., 2003). The success of the model in predicting nitrogen release under albizia and in bare soil – where populations were measured – supports this claim.

In general, the model was successful for some residues but not for others, suggesting that a fixed C/N ratio as the only quality parameter might not be sufficient to explain differences in mineralization rates and patterns of different plant materials and indicating the need to include observed soil populations for all plant materials considered. Since the performance of the model was satisfactory for albizia, we proceeded to use the model to test the hypothesis that the change in soil community brought about by the addition of albizia prunings influences nitrogen mineralization.

Effect of Changes in the Soil Biota on N Mineralization

Including the changes in the soil community caused by the addition of prunings increased the mineralization rate and soil nitrogen concentrations and therefore the model's ability to predict nitrogen mineralization rates and soil nitrogen concentrations. The main changes induced by albizia prunings additions were larger total community biomass, greater relative importance of fungi in the microbial community and larger proportion of fauna (protozoa, nematodes and microarthropods) as a percentage of the whole community. Higher simulated mineralization rates and N concentrations are expected given the larger population sizes of soil organisms, which constituted the main effect of residue addition on the soil community. Larger biomass pools imply more consumption demand and therefore more N released in inorganic form with every mass transfer.

An important finding of this study is the enhancing effect of residue on fungal biomass. Fungi tend to have a better ability than bacteria to process resistant substrates and mobilize the N contained in them (Paul and Clark, 1996). Also, fungi generally have a higher C/N ratio (Wardle, 2002), which provides them with lower N demand levels resulting in greater amounts of released N. Greater N mineralization rates would then be expected if fungal biomass increases. This is consistent with both the observed and simulated patterns. Members of the mesofauna have been shown to enhance nutrient mineralization in soil (Coleman et al., 2004). An increase in fauna's representation in the soil community would then be expected to increase nitrogen mineralization rates. This was also consistent with observed and modeled results.

Improving the prediction of nitrogen mineralization by incorporating the soil community supports our initial hypothesis and indicates that taking into account the soil biota structure and dynamics – in addition to biochemical quality – is important for explaining short-term mineralization patterns from green manures and other plant residues in alley-cropping systems. This research highlights the importance of understanding how the role of soil organisms in the mineralization process can be affected by management. As the success of alley-cropping systems relies to a large extent on their nitrogen cycling, this understanding can be key in enhancing their sustainability.

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Chapter 17

Separating the Tree–Soil–Crop Interactions in Agroforestry Parkland Systems in Saponé (Burkina Faso) using WaNuLCAS

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Z. Teklehaimanot[3], and S.J. Ouedraogo[1]

Introduction

Trees in the parkland systems of West Africa are important for farmers because they provide food and income. However, they also interact with the grain crops, positively as well as negatively. Trees and associated crops differ in their ability to capture and use the most limiting essential growth resources effectively (Monteith, 1981). Thus, competition and complementarity in resource use between the components of parkland systems need to be better understood. These processes occur both above- and belowground as plants balance the aboveground water loss and carbon gain with the belowground access to soil supply of water via the roots. In mixed communities plants rarely compete for light without simultaneously competing for water and nutrients (Ong, 1996; Mobbs et al. 1998; Kho, 2000a,b) and our understanding of how mixed species systems grow and utilize resources will remain restricted unless experiments are designed which explicitly recognize this (Wallace, 1996). The present research was, therefore, designed to study the effect of crown pruning on the productivity of agroforestry parkland systems in terms of resource capture and utilization. The focus was on two species of trees *Vitellaria paradoxa* C.F. Gaertn (karité) and *Parkia biglobosa* (Jacq.) Benth. (néré), both producing high-value fruit.

Previous results showed no significant difference in millet performance between the zone under unpruned trees of both tree species and the zone in the open area (Jonsson et al. 1999). According to Jonsson et al. (1999), the negative effect of tree shade must have been compensated for by improvements in crop temperature and soil

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S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*

fertility. The importance of the positive soil fertility effect is seen in crops (sorghum, millet) responses to severe pruning of the trees (Kessler, 1992; Bayala et al. 2002).

Where the overall positive effect through soil improvement can be estimated by inference, the experimental data do not allow a separation of above- and belowground resource interactions as components of the overall competition effect (Ong, 1996; Kho, 2000a,b).

The lack of understanding the balance of positive and negative interactions between the 'tree' and 'crop' components, and that between 'vegetative parts of the tree' and 'fruit production by the tree' may limit our ability to fully evaluate and help improve farmer management practices. The main question in the present study was how do trees and crops influence each other via the main resources limitations. The approach used to get an insight of the relative contributions of each growth resource was a combination of field control for light using crown pruning and modeling for water and nutrients using WaNuLCAS2.0 (Van Noordwijk and Lusiana, 2000). Such knowledge has important implications for the management of karité and néré parklands.

Materials and Methods

Study Site

The study was carried out in the parklands of Saponé, a village located 30 km south of the city of Ouagadougou, Burkina Faso, West Africa (12°03′ latitude North and 1°43′ longitude West) and at an altitude of 200 m.a.s.l. The parklands of Saponé are dominated by the two major tree species of sub-Saharan African parklands: karité (*Vitellaria paradoxa* C.F. Gaertn.f.) and néré (*Parkia biglobosa* (Jacq.) Benth). The rainfall is uni-modal with a mean annual rainfall of about 721 mm. The rainfall for 1999, 2000 and 2001 rainy seasons were 805, 680, and 931 mm, respectively. The soils are sandy loamy Regosols (Pallo, 2001), with very low nutrient content (N = 0.03%, extractable P = 1.05 ppm, and exchangeable bases $<2.5\,\text{cMol}_c\ \text{kg}^{-1}$) (Jonsson et al. 1999).

Tree Selection and Pruning

Nine mature trees, which were ≥30 cm in diameter and bearing fruit, each of karité and néré (total 18 trees) were randomly selected in January 1999 in farmers' fields. Discussions were held with the farmers, who are the owners of the trees and those who cultivate crop by borrowing land from the owners of the trees, to obtain their agreement to carry out the research. Tree characteristics were measured on all 18 selected trees (Table 17.1).

Table 17.1 Characteristics of tree samples selected for the study (Mean ± SE) in an agroforestry parkland system in Saponé, Burkina Faso

	Height (m)	Trunk height (m)	DBH (cm)	Crown diameter (m)	Crown projection area (m^2)
Karité	11.67 ± 0.43	2.1 ± 0.08	49.76 ± 2.50	10.56 ± 0.34	90.21 ± 5.78
Néré	15.38 ± 0.43	2.21 ± 0.07	89.06 ± 5.00	20.98 ± 0.68	356.34 ± 22.42

Table 17.2 Tree and crop management schedule in an agroforestry parkand systems in Saponé, Burkina Faso

Year	Month	Day	WaNuLCAS Day	Activity
1999	May	26	146	Pruning
	June	10	161	(1st cropping) Sowing millet
	October	22	295	Harvest millet
2000	June	17	168	(2nd cropping) Sowing millet
	June	25	176	Harvest fruit of néré
	August	18	228	Harvest fruit of karité
	October	15	288	Harvest millet
2001	June	5	156	(3rd cropping) Sowing sorghum
	June	23	174	Harvest fruit of néré
	August	19	231	Harvest fruit of karité
	October	17	290	Harvest sorghum

No fertilizer was applied

The various ways that farmers prune parkland trees can be grouped (Timmer et al. 1996) into two categories: partial and total pruning. Taking this into account, the following treatments were applied to the sample trees in May–June 1999 by agreement with the farmers: 6 unpruned (control), 6 half-pruned (50% of the crown removed), and 6 totally pruned (100% of the crown removed) (Table 17.2). The removal of 100% of the crown was achieved by reducing all of the secondary branches to one meter from their bases and the removal of 50% of the crown involved similar reduction but applied only to half of the secondary branches. After pruning the mean crown diameter of totally pruned néré trees was 11.6 ± 1.1 m and karité 3.4 ± 0.7 m. However, pruning 50% of the crown of both species did not modify crown diameter.

Field Experiment Data Collection

The effects of crown pruning of karité and néré on above- and belowground interactions with associated crops of *Pennisetum glaucum (L.)* (millet) and *Sorghum bicolor* (L.) Moench (sorghum) were investigated. To do so, the area under each tree was divided into four concentric tree influence zones before pruning the trees (Zones A: up to 2 m from the tree trunk, B: up to half of the radius of the tree crown, C: up to the edge of the tree crown and D: up to 2 m away from the edge of the tree

Table 17.3 Thickness (m) and width (m) of soil layers of agroforestry zones in a parkland system in Saponé (Burkina Faso) used for experiment and simulations with WaNuLCAS

		Karité			Néré		
Layer/ Zone	Soil layer thickness (m)	Unpruned	Half-pruned	Totally pruned	Unpruned	Half-pruned	Totally pruned
1	0.1	2	2	2	2	2	2
2	0.1	0.92	1.38	0.6	2.92	2.9	3
3	0.1	2.96	3.39	2.09	4.93	4.9	5.1
4	0.2	2	2	2	2	2	2

crown). In these zones (Table 17.3), measurements of crop performance at harvest, light through out the cropping season (Bayala et al. 2002), nutrient status once in 1999 and root distribution through out the cropping season were made under the 18 trees for both species (Bayala et al. 2004).

Simulations

WaNuLCAS Features

WaNuLCAS is a generic model for water, nutrient, and light capture in agroforestry systems (Van Noordwijk and Lusiana, 1999; 2000). The model is formulated in STELLA Research modeling environment with an emphasis on belowground interactions. In this model, competition for water and nutrients (nitrogen and phosphorus) is based on the effective root length densities of both plant components and current demand by tree and crop. This model has been used by many workers among whom we want to mention Cadish et al. (1997) who explored the safety-net hypothesis with WaNuLCAS, Suprayogo et al. (2002) compared simulated data of WaNuLCAS and field measurements on N leaching and Smith et al. (2004) explored water competition in agroforestry systems.

The WaNuLCAS model consists of two parts, i.e. WaNuLCAS.xls workbook for deriving model parameters and WaNuLCAS.stm file for dynamic simulation. Simulations require the prior definition of a soil profile in four layers of variable thicknesses that can be defined within the model (Table 17.3) as well as soil physical and chemical properties per layer.

Agroforestry systems are defined on the basis of four horizontal spatial zones (Table 17.3) within which water, nitrogen, and phosphorus balances and uptake by crops and trees can be examined. It is assumed that tree occupies the first zone close to its trunk and the three remaining zones are occupied both by tree and the crop. The combination of four zones and four depths gives 16 compartments for which the soil properties must be defined. The model incorporates management regimes such as tree and crop species, tree-pruning, fertilizer use, etc.

Model Inputs

The site-specific parameters data used for setting up the simulations in the present study included soil texture, soil bulk density, and saturated hydraulic conductivity as basis for the pedotransfer functions for further soil and water parameters required to produce various outputs. Soil chemical properties (soil organic matter, nitrogen and phosphorus content), tree and crop management parameters (planting dates, pruning dates by specifying the years and days of the years), tree (growth parameters, aboveground architecture, pruning treatments, and root densities), and crop parameters (growth parameters and root densities) were also included. Most of all the inputs were entered in WaNuLCAS.xls file linked to WaNuLCAS.stm file. Inputs entered into the STELLA file included monthly rainfall of the 3 years (1999, 2000, and 2001) and soil temperature as well as agroforestry zones and thicknesses of layers as shown in Table 17.3. If some calendar events (dates of pruning, dates of sowing, etc.) were entered in the model, other were triggered internally; for example, crops were 'harvested' in the simulation based on the specifications of their vegetative and generative phases as defined in the 'Crop Type' section WaNuLCAS.xls file.

As WaNuLCAS can not simulate all the three pruning treatments (no-pruning, half-pruning, and totally pruning), each treatment was simulated separately by switching off the others.

Data Analysis

A comparison of crop performance under unpruned and totally pruned trees was undertaken to reveal the importance of light as growth resource. However, because of the evident combination of above- and belowground interactions in the parklands, further determination of the relative importance of the remaining growth resources was explored with the WaNuLCAS model. The empirical data were compared with a series of simulations made with the Water Nutrient and Light Capture in Agroforestry Systems model (Van Noordwijk and Lusiana, 2000). The simulations provided predictions of millet and sorghum yields for each of the 3 years and for each of the experimental treatments (pruning intensities). An excel table was therefore created within the model into which the daily information for tree and crop biomass generated during the simulations were copied. These data were regressed against the measured ones using Minitab Release 12 Statistical Package.

The limitation for a particular growth resource was based on the number of days during which trees or crops have experienced a stress linked to that resource. This number was later expressed as a percentage of the simulation time (year for tree and cycle duration for crop).

Model performance relative to the empirical data was evaluated through a number of summary statistics (Table 17.4): Maximum Error (ME), Root Mean Square Error (RMSE), Coefficient of Determination (CD), Modeling Efficiency (EF), Coefficient of Residual Mass (CRM), Slope (S) of regression equation (Simulated = S^*Measured).

Table 17.4 Statistical criteria for evaluation of model results according to Loague and Green (1991)

Criterion	Symbol	Calculation formula	Range	Optimum
Maximum error	ME	$\mathrm{Max}\lvert Pi - Oi\rvert^{n}_{i=1}$	≥0	0
Root mean square error	RMSE	$[\sum_{i=1.n.}^{n} (P_i - O_i)^2]^{1/2.} * 100.O_{mear}$	≥0	0
Coefficient of determination	CD	$\dfrac{\sum_{i=1.}^{n} (O_i - O_{mean})^2}{\sum_{i=1.}^{n} (P_i - O_{mean})^2}$	≥0	1
Modeling efficiency	EF	$\dfrac{[\sum_{i=1\,i=1}^{n\,n} (O_i - O_{mean})^2 - \Sigma (P_i - O_i)^2]}{[\sum_{i=1.}^{n} (O_i - O_{mean})^2]}$	≤1	1
Coefficient of residual mass	CRM	$\dfrac{[\sum_{i=1\,i=1.}^{n\,n} O_i - \Sigma\ i]}{[\sum_{i=1.}^{n} O_i]}$	≤1	0

P_i = predicted value of i; O_i = observed value of i; O_{mean} = mean of observed values; n = number of data pairs

Results and Discussion

Results of Field Experiments

The results showed that crop performance did not increase as light supply increased going from the tree trunk to outside the canopy (Figures 17.1 and 17.2). This is probably linked to the higher soil fertility under trees (Tomlinson et al. 1995; Bayala et al. 2002), and lower soil and air temperature under trees (Jonsson et al. 1999). The present trend may also be due to the competition from belowground for water and nutrients. On the other hand when light supply was increased, by removing the tree crown, crop performance was significantly improved showing that under trees this factor is the most limiting. (Figures 17.1 and 17.2). Pruning also reduced the rates of water transpired by trees (Bayala et al. 2002) and this reduction was certainly associated with changes in the use of nutrients indicating the need to further separate the effects of water and nutrients (N and P).

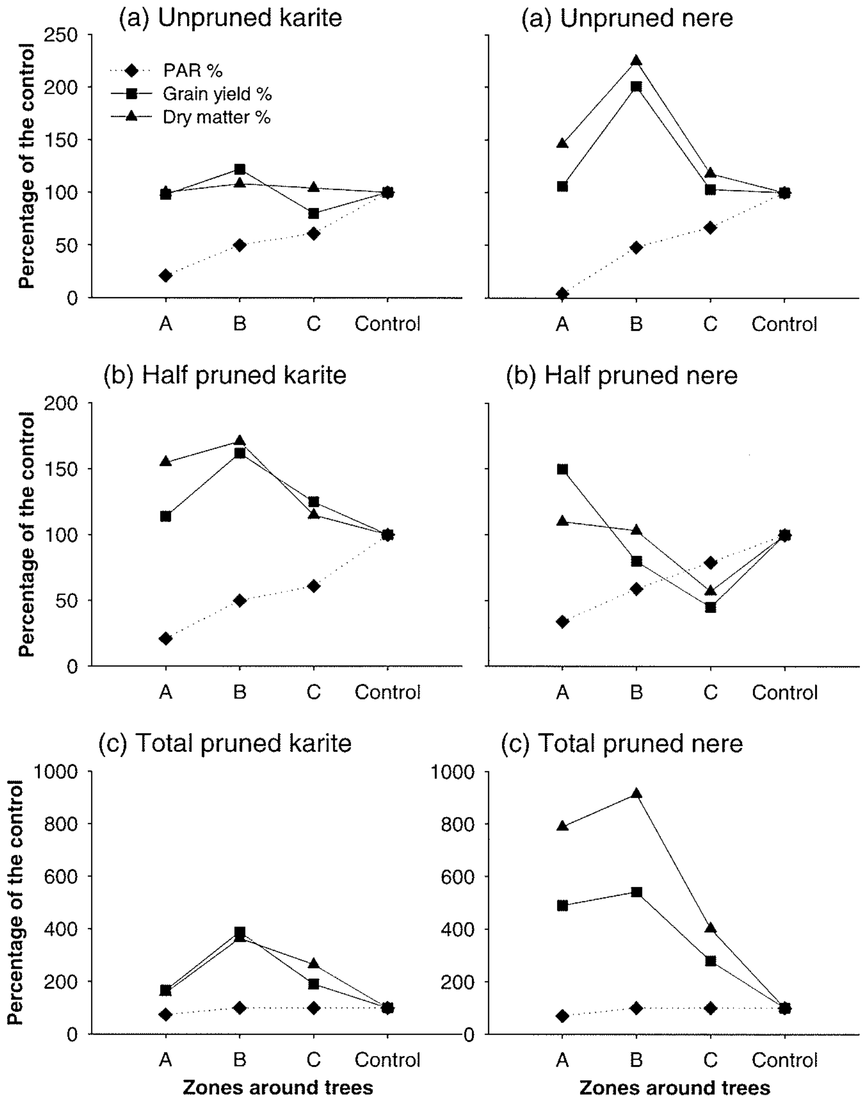

Figure 17.1 Pattern of pearl millet performance in relation to light under karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees in a parkland agroforestry system. (From Bayala et al. 2002.)

Simulations

As shown in Table 17.5, the slopes (S) of all the regression equations established between simulated data and measured data were very highly significantly different from 0 (all $P < 0.001$). However, crop performance for the various zones and pruning

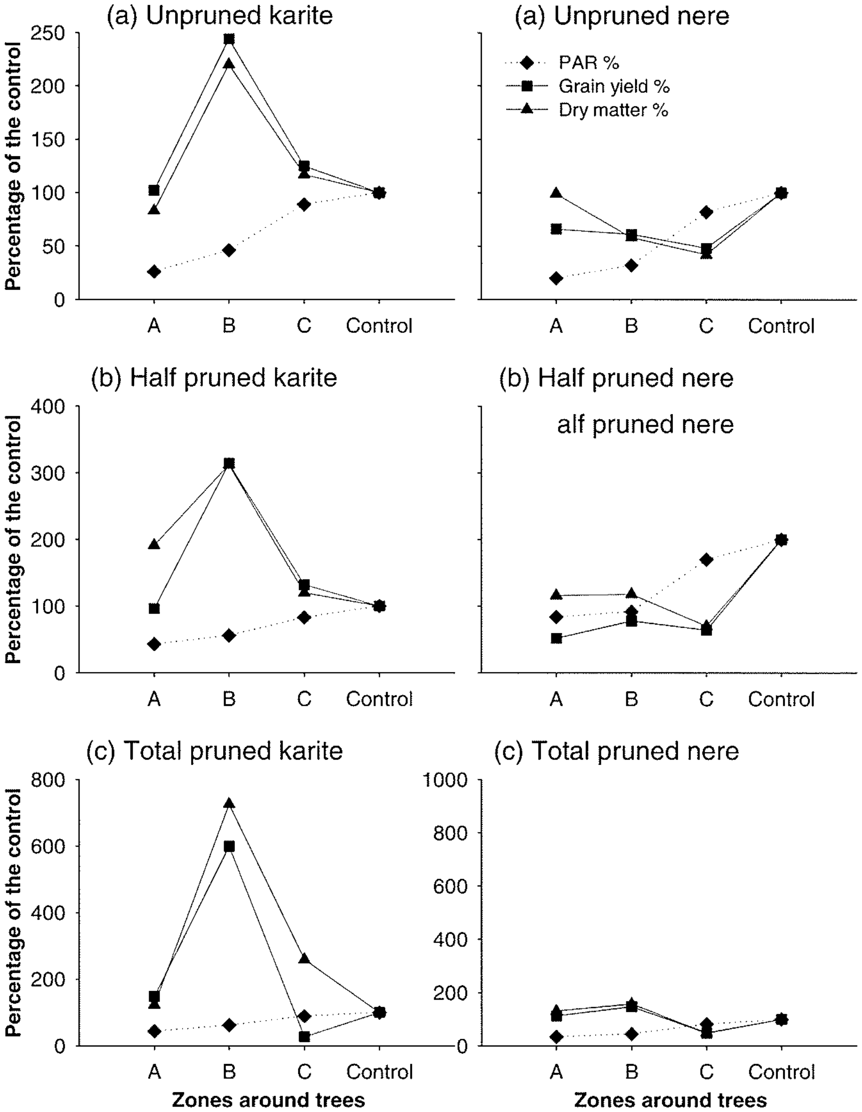

Figure 17.2 Pattern of sorghum performance in relation to light under karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees in a parkland agroforestry system

regimes tended to be overestimated according to statistical criteria for evaluation of model results (see EF in Table 17.5, Figure 17.3). That indicates that not all limitations occurring in the field were adequately represented and/or that resource capture for the resources included in the model (light, water, N, and P) was overestimated. Model performance on total crop biomass was much better than that on harvestable

Table 17.5 Model performance statistics for grain yield (Yield) and total dry matter (TDM) of crops under karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees in a parkland agroforestry system in Saponé, Burkina Faso

	Crop production (kg m^{-2})				
	Karité Yield	TDM	Néré Yield	TDM	Optimum
N	27	27	27	27	–
ME	0.1	1.2	0.1	0.5	0
RMSE	453	17	214	3	0
CD	1	13	1	3	1
EF	0.2	0.9	0.3	0.7	1
CRM	–0.3	0.1	–1.5	–0.4	0
S	1.01***	0.51***	1.74***	0.86***	1
R^2	0.78	0.55	0.69	0.59	1

N = number of observations; ME = Maximum Error; RMSE = Root Mean Square Error; CD = Coefficient of Determination; EF = Modeling Efficiency; CRM = Coefficient of Residual Mass; S = slope of the regression equation (Simulated = S * Measured); R^2 = Correlation coefficient.

*** $P<0.001$ for the statistical test for difference from a slope (S) of 0 was very highly significant for all regressions equations (all $P<0.001$).

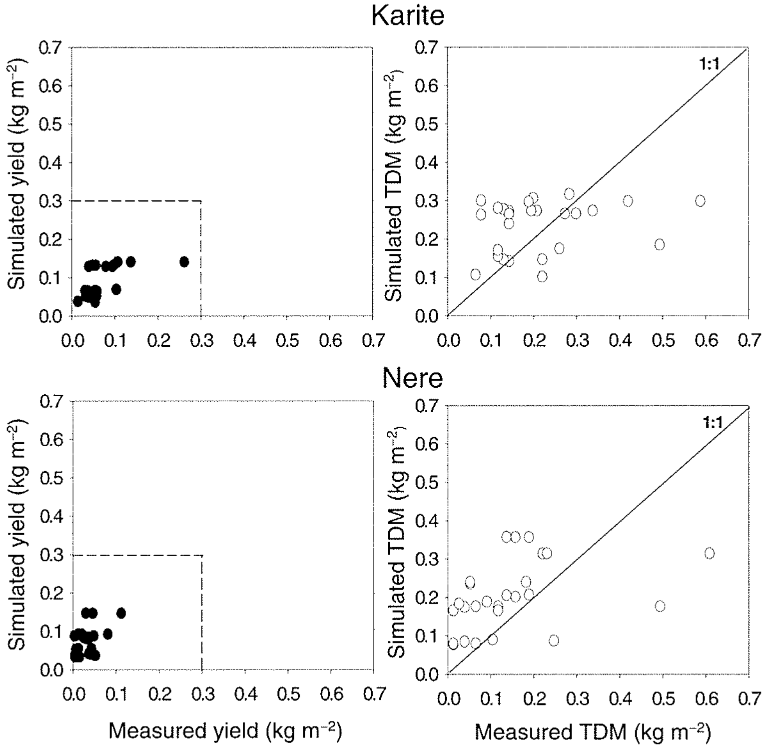

Figure 17.3 Scatter plots of measured and simulated crop yield and total dry matter (TDM) under karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees in a parkland agroforestry system in Saponé, Burkina Faso

yield, and there appear to be some major problems with the default parametization for millet in this regard. Simulation with WaNuLCAS indicated that the plant components differed in the key limiting factors.

For karité, with a relatively shallow root system, simulated water limitation dominated for 27%, 25%, and 29% of the simulation period for unpruned, half-pruned and totally pruned trees, respectively. Water limitation was also found to restrict crop growth under this species (20% of the simulation time in unpruned and half-pruned trees and 24% of the growing season for totally pruned). P limitation restricted totally pruned tree for 48% of the season and crop growth only 8% of the season in unpruned and half-pruned trees and 5% in totally pruned trees. The P limitation, which appeared in totally pruned karité may be due to the fact P-transport to roots is decreased by decreases in soil water content due to better crop development (Ong et al. 2004). Water limitation in karité is probably due to its shallow root system indicating its high dependency on rainfall water and probable less access to the groundwater table. Secondly, this species bears branches, which usually have an upright habit (Bonkoungou, 1987; Hall et al. 1996). Such architecture allows more light to reach underneath tree inducing a better crop production compared to néré (Bayala et al. 2002). Therefore, better crop development under karité leads to higher competition for water because the water 'saved' by reduction in soil evaporation by this species is less important compared with the situation under néré. Thus, water limitation is the most important factor after light followed by phosphorus, this later factor becoming more severe for totally pruned karité trees. Such change in phosphorus limitation suggests that this nutrient must be supplied when karité is totally pruned. No nitrogen limitation was found for either tree or crop growth probably because of the higher soil nitrogen content in the influence zone of trees (Kessler, 1992; Kater et al. 1992; Bayala et al. 2002).

For the néré tree, the main limitations were water (never for unpruned trees, 2% of the simulation period for half-pruning trees, and 14% for totally pruned trees) and P (16% for unpruned and half-pruned trees and 60% of the simulation time for totally pruned trees). Similar to karité, pruning also rendered more severe the P-limitation in néré indicating that the production of new shoots of pruned trees is highly P demanding. Another explanation may be that a better development of associated crops makes them more competitive for P thus increasing the limitation for the pruned trees. Crop growth under néré was mainly limited by P (43% of the simulated growing season for unpruned trees, 51% for half-pruned, and 22% for the totally pruned trees) corroborating the findings of Tomlinson et al. (1995) and Bayala et al. (2002). These authors found lower P content under this species compared with the outside zone and that may be due to néré high demand in this element thus depleting this element which becomes more limiting after light under this species. In turn, the poor development of crop under this species (Bayala et al. 2002) associated with its deeper root system accessing to the water table may explain why water did not appear so limiting for associated crops. Furthermore, a better growth of associated crops under pruned nérés (as well as under karités to a less extend) was associated with a better development of crops root systems (Bayala et al. 2004) enabling them to acquire the phosphorus and therefore reducing the P-limitation for crops under néré pruned trees. Again as under karité, no nitrogen limitation was found in néré may be because of the same reasons as for karité.

The results of the present study show that limitation did not involve only one resource but the three main resources (light, water, and phosphorus) even though the degree of the limitation differs from one species to another and also between pruning treatments. Such result is in agreement with Ong et al. (2004). The lack of limitation for nitrogen may be due to the contribution of trees in the availability of this element through the recycling of tree litter corroborating Kho (2000b). In fact, Bayala et al. (2002) found a strong correlation between C and N which indicates that the main source of C and N may be the trees as crop residues are always removed from the land at harvest by farmers. Thus, the strong correlation between C and crop performance may indicate the positive effect of trees on soil amelioration as reported by Bayala et al. (2006). These authors, using natural ^{13}C tracer technique showed a very significant higher contribution of trees to soil carbon in their influence zones compared to C_4 plants (crops and weeds) with a clear and significant decreasing trend going from tree trunk to the open area in the same experiment. Moreover, nitrogen may not be limiting for the low crop production in semi-arid zones because of strong net mineralization at the start of the cropping season (Kho et al. 2001).

The trend of the limitations for water and nutrients as revealed by simulations with WaNuLCAS can help in future field experiments aiming at controlling resource use effects.

Conclusions

The results of the present study show that light is the main limiting factor for associated crops under both karité and néré whereas no limitation was found for nitrogen. The main limiting factor was water for karité and phosphorus for néré whereas no nitrogen limitation was found for both species.

The WaNuLCAS model overestimated crop performance but it appeared to be a good tool for efficiently synthesizing experimental information on tree and crop interactions allowing further separation of the effects of growth factors for agroforestry parkland systems.

WaNuLCAS prediction of fruit production by the tree could not yet reproduce the measured effects of tree pruning. Further details of tree phenology and canopy recovery on the basis of stored growth reserves in the tree need to be investigated.

Acknowledgments The field work of this study was funded by the European Commission, Directorate General XII, under the program of INCO-DC: International Co-operation with Developing countries (1994–1998), the International Atomic Energy Agency, through the project: 'Lutte contre la désertification au Sahel', the International Foundation for Science (IFS). IFS also sponsored our participation to the World Agroforestry Congress. The modeling phase was jointly sponsored by TWAS-UNESCO and ICRAF-SE. We wish to thank the farmers in Saponé for their permission and participation in the field experiment, and also Koté Lansina and Belem Achille for field assistance.

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Section 5
Synthesis

Chapter 18

Applying Ecological Knowledge to Agroforestry Design: A Synthesis

A.M. Gordon[1,*] and S. Jose[2]

Introduction

The universal application of ecological principles to agroforestry system design and management is nearly impossible as a result of the many varied types of systems in existence – from riparian management systems that link terrestrial and aquatic systems to more traditional systems that integrate perennial plants with annual crops, with or without animals. The broad geographical range over which agroforestry systems may be successfully implemented and the scale at which interactions occur – from landscape to individual plant – also complicates the development of an universal understanding of nutrient and energy flows and the relationship of these to system productivity. Indeed, this sentiment is underscored by the research results presented in various chapters in this book: examples are given of systems that vary in the degree of uncertainty of system predictability and repeatability. Nonetheless, a quick review of the chapters will leave us with a broad understanding of perhaps where future research and management efforts should be concentrated.

Synthesis

Chapters in Section II draw our attention to aboveground processes in four major agroforestry systems. In Chapter 2, Oelbermann et al. documented changes in the biophysical environment of a riparian system over a 16-year period following establishment of a treed buffer strip. Not surprisingly, changes were observed in many common ecosystem-level structural and functional parameters, from indicators of biodiversity to many common nutrient fluxes, such as that defined by streambank

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litterfall. The research in this Chapter, and that of Mize et al. (Chapter 3) on windbreaks underscores two important concepts, sometimes lost in the search for specific tree–crop interaction at the level of physiological response: time and space (scale). We tend to forget that, with the exception of some agroforestry systems where the perennial tree component is routinely coppiced, one of the greatest attributes of agroforestry systems is the relatively long and important role that trees play in regulating ecosystem function. In the case of both integrated riparian systems and windbreaks, the linear nature of these systems also means that this role is important at both a very local scale (e.g. impact of shade on stream temperatures, impact of windbreaks on soil erosion) and at the landscape level. In the latter case, disparate woodlands in a fragmented landscape may be joined by riparian or windbreak corridors, providing important habitat for animals, birds and insects. For an overview on riparian and windbreak systems in a temperate setting, the reader is referred to Schultz et al. (2004) and Brandle et al. (2004), respectively.

Chapters 4 and 5 explore particular physiological relationships related to crop–light regime interactions in silvopastoral systems. Both sets of authors, while working in very different circumstances (Feldhake et al. – temperate; Baligar et al. – tropical) explored forage yield in relation to shade production, concluding generically that matching crop species to appropriate shade levels, as ultimately determined by planting density of the tree component, would result in improved forage yield, soil and water conservation and perhaps sward composition. Research of this nature (e.g. Knowles et al., 1998) is largely driven by the need to ensure that system animals (herbivores) have access to sufficient net primary production in the sward component, as the latter is obviously affected by the presence of trees in the system. Research on ecosystem-level processes in silvopastoral systems such as litter decomposition (Wedderburn and Carter, 1999), root competition between tree and herb components for nutrients (George et al., 1996) and carbon storage and nutrient cycling (Kaur et al., 2002) is less common, especially in the temperate region, but obviously vital to a comprehensive understanding of these very useful systems.

Some basic ecological relationships with respect to microclimate modification are investigated in Chapters 6 (Zamora et al.) and 7 (Shapo and Adam). Although the research of the former was ultimately aimed at understanding the impact of shading on intercrop production, it was actually belowground competition (see Section III) that was found to be limiting intercrop production: when eliminated, cotton production in alleys between pecan trees was comparable to that found in sole-cropping systems. This underscores an important point: competition vectors above and belowground in alley-cropping systems are, because of variable ecological niches occupied by trees and crops when grown together, decidedly more complicated and information is emerging that would even suggest that they are closely linked. A systems approach to studying any agroforestry system will greatly enhance our ability to capture the most important ecological information necessary to design and manage productive systems. This is probably most true for intercropping systems (cf. Thevathasan and Gordon, 2004).

The final two chapters in this section deal with resource allocation in Central American agroforestry systems. Bellow et al. (Chapter 8) report that annual crop yields were unaffected by overstory shade treatments in fruit tree-based intercropping systems, making fruit yield from overstory trees an important additional benefit over ‘crop only’ treatments. This was likely a result of the ability of the mixed system to capture additional quantities of both above- and belowground resources. In Chapter 9, Vaast et al. investigated coffee production in the presence of shade produced by two intercropped timber tree species. A more favourable microclimate as represented by lower air temperatures of 2–4 °C increased bean size, improved bean composition and cup quality by lengthening the maturation of coffee berries. These two papers collectively indicate the complexity of understanding shade–crop productivity relationships. In some cases, positive or neutral interactions can be observed, while in other situations the opposite can be seen. Belowground resource accumulation (e.g. carbon and nitrogen) associated with positive understory yields have been reported elsewhere; Isaac et al. (2005), for example, demonstrated this in West African multistrata cacao systems.

In the temperate zone, shade may reduce yields of crops, especially of C_4 plants, but may also decrease evapotranspiration fluxes from the crop, especially under drought conditions, thus providing some, but reduced yield. Managing for shade is also difficult: a single management operation – pruning – will indeed reduce shade, but at the cost of the ability of the tree to produce litterfall. Thus, one single management option affects two interactions simultaneously – one positive (litterfall) and one negative (shade). The relationship between shade production, photosynthetic parameters and yield is complicated (e.g. Zamora et al. 2006; Reynolds et al. 2007) and varies greatly amongst systems. Nonetheless, there is a continued need for additional information on the physiological interactions at work in intercropping, and to a certain extent, silvopastoral systems.

Resource allocation and related ecological processes belowground are dealt with formally in Section III. In Chapter 10, Kiparski and Gillespie investigated long-term belowground and aboveground competition between black walnut trees and corn. They argue that the management inputs necessary to maintain crop productivity are reflected in overall productivity (crop and tree) and landscape-level conservation effects. Gowda and Kumar (Chapter 11) tested the hypothesis that root competition in multi-species systems depended more upon the belowground growth traits of the trees than resource availability. They accepted this hypothesis, illustrating that a solid understanding of long-term morphological growth patterns in trees in concert with companion crop phenology is critical to the successful design of intercropped systems. Reuter et al. (Chapter 12) alleviated competition for water in a limited rainfall region of southern Mexico by sporadic irrigation, indicating that, with available technology, concerns about limited productivity as a result of belowground competition can be alleviated. This approach is not always possible for financial or other reasons. Finally, in Chapter 13, Mafongoya and Hove discuss the interaction that polyphenolic compounds of tree-origin have with important soil processes, such as nitrogen mineralization, but indicate that an understanding of mechanism remains elusive.

Modelling efforts and other analytical tools are coming of age with respect to the broad field of agroforestry and some of these are discussed in Section IV. Kimmins et al. (Chapter 14) suggest that while agroforestry systems have enjoyed great success historically, only process-based understanding in combination with experience-based knowledge of agroforestry systems will allow us to predict the outcomes of untested new systems before they are implemented. As they put it: 'Designing for change in agroforestry may also require an understanding of the details of the mechanism responsible for the productivity, sustainability and environmental services provided'. In Chapter 15, Righi et al. extol the virtues of utilizing light attenuation models in concert with assessment of Leaf Area Index to understand light – crop productivity relationships in coffee–rubber systems. Carillo and Jordan (Chapter 16) use a soil food web model to simulate nitrogen mineralization patterns in the alley of an intercropping system, finding that pruning additions of *Albizia* greatly influenced the soil biotic community, by increasing, for example, the relative importance of soil fungi. Finally, The WaNuLCas model is utilized in Chapter 17 by Bayala et al. in West African tree–cereal systems. The model allowed for the separation of factors affecting crop growth and fostered research deign aimed at controlling component effects. Indeed, one of the best attributes of even simple models lies in their ability, when properly utilized, to control interactions and effects in multi-flux systems in order to isolate and understand in greater detail specific processes of interest.

Research Gaps and Key Questions

Collectively, the 16 chapters described herein, have all addressed ecological parameters in many different types of agroforestry systems and at many scales – from that of the landscape to that of the physiological environment. While it is true that an ecosystem-level approach to implementing agroforestry systems requires ecosystem-level knowledge, it is equally true that day-to-day management decisions in operation require detailed physiological data specific to the components under study, and it is not our purpose here to suggest that research of one kind is more important than another.

At a large scale, information is required on the landscape level effects of system implementation. For example, with respect to windbreaks, ecological impacts often seen at the stand level may or may not be seen at the landscape level. It may be possible to model this, but empirical landscape-level response data are also required. This would also be true for all of the major agroforestry systems.

Although productivity is often referred to throughout the text, it is rarely documented, either here or in other studies. It is important that agroforestry systems be described in terms of net primary productivity (increment + litterfall + herbivory + mortality). Beyond an understanding of yield, this will allow for the comparison of different agroforestry systems with other common land-use practices, and such comparisons can provide extreme insight into larger questions, such as climate change and the role of tree-based systems to mitigate this.

With respect to integrated riparian management systems, more ecosystem-level processes need to be investigated. Perhaps a good way to approach this is to think about the plethora of information that has been generated from the many years of investigation at Hubbard Brook (Bormann and Likens, 1979) where forested watersheds were deforested and system level responses, in terms of water chemistry and other parameters, evaluated. Integrated riparian management is the opposite, placing trees in varying buffer widths back on a landscape previously deforested (see Oelbermann et al. Section II; Schultz et al. 2004). Although expensive, more studies of this type need to be implemented and done in conjunction with the appropriate economic studies necessary to evaluate the wood production component of the system.

In both silvopastoral and intercropping systems, continued acquisition of information on interaction between system components at a range of scales is urgently needed. Shade-yield studies need to be expanded to embrace interactions between trees and crops that have proven their adaptation to coexist. This information is needed to update management strategies, to add ecological foundation to the design component of agroforestry and to provide a sound basis for modelling efforts that may encourage the future use of agroforestry for a variety of purposes. Obviously, data on belowground ecological processes (e.g. nutrient competition, root distribution patterns (e.g. Jose et al. 2000; Gray, 2000; Zamora et al. 2007), microbial–tree root interactions (e.g. Dougherty et al. 2006), dynamics of earthworms (e.g. Price and Gordon, 1999) and other soil organisms, etc.) are also urgently needed. Simultaneous economic studies need to embrace not only components of yield (crop, tree and animal), but the ecological net worth of these systems, again at a multitude of scales. In the case of silvopastoral systems explicitly, more research is needed on the physiology of animal–tree interactions; this will allow for the evaluation of these systems with respect to the important and emerging issue of animal welfare.

With respect to greenhouse gas (GHG) emissions, all agroforestry systems will benefit from comprehensive studies of the carbon budget that look at balancing emissions with sequestration strategies. These studies need to be conducted at multiple latitudes, in order to capture the increased respiratory costs associated with warmer climes, and the suggested more rapid change of climate in more northerly regions. In this regard, silvopastoral systems utilizing ruminants represent a particular interesting challenge. Management decisions concerning animal and tree stocking density need to be made in light of well-documented studies on C-sequestration (trees and soils) that are potentially offset by methane emissions from the animal component (Gordon and Thevathasan, 2005). The interaction of animal welfare and GHG research comes in an appreciation for potential reduced emissions from animals in a healthier environment. Specific research is needed on this.

The ecological viewpoint has been espoused for many decades as a solid framework within which to understand the interactions of species and other system components in complicated natural systems (cf. Balch, 1965). This framework will also serve the science of agroforestry well, as we attempt to understand the cycling of nutrients, the flow of energy and the level to which management interventions will change these processes within the myriad of systems that agroforestry comprises. We invite the scientific community to embrace the ecological viewpoint as it relates to the historical and emerging field of agroforestry.

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