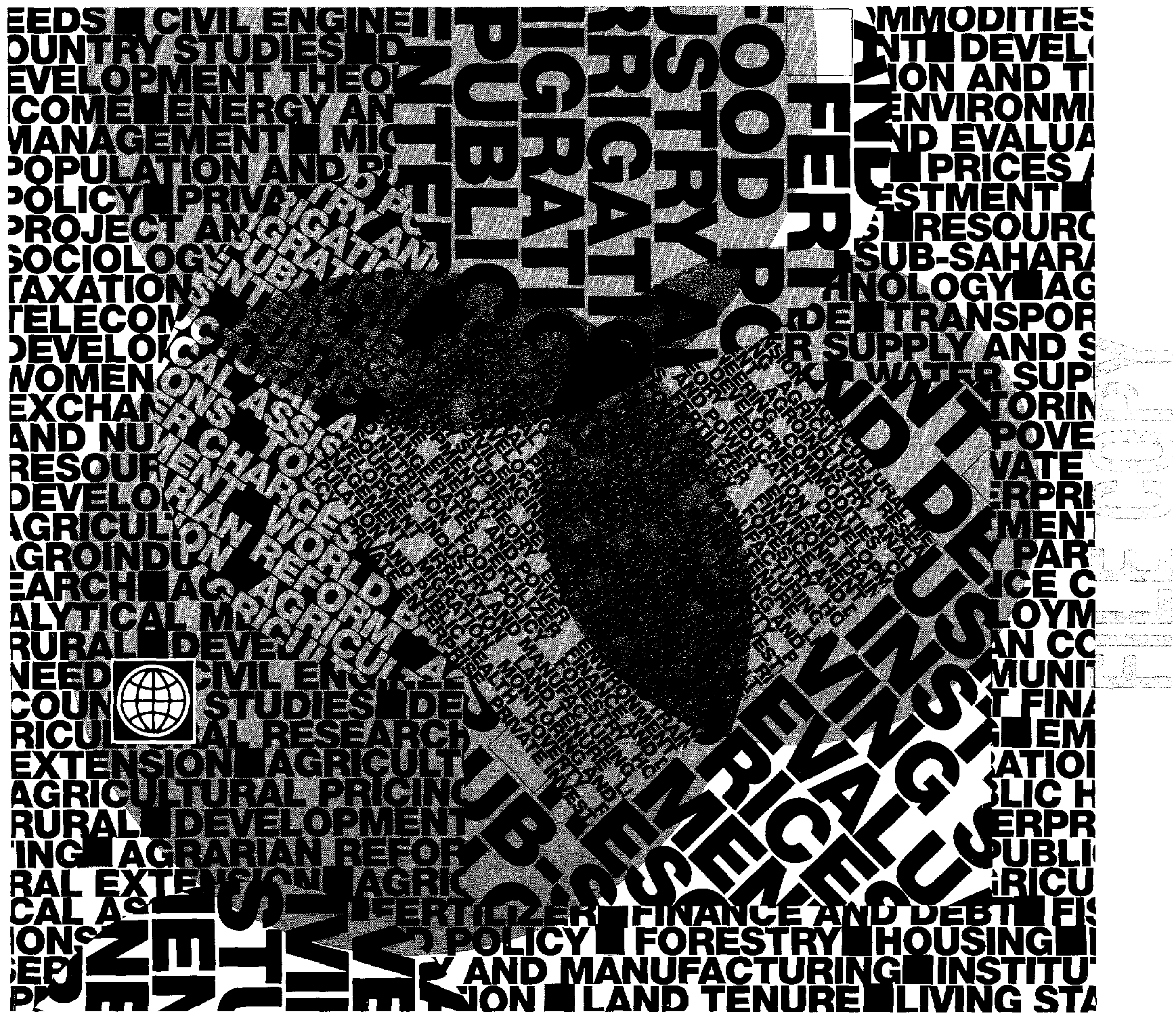
WTP- 131

WORLD BANK TECHNICAL PAPER NUMBER 131

The Prospects for Agroforestry in the Tropics

P.K.R. Nair



RECENT WORLD BANK TECHNICAL PAPERS

No. 68 Armstrong-Wright and Thiriez, *Bus Services: Reducing Costs, Raising Standards*

No. 69 Prevost, *Corrosion Protection of Pipelines Conveying Water and Wastewater: Guidelines*

No. 70 Falloux and Mukendi, *Desertification Control and Renewable Resource Management in the Sahelian and Sudanian Zones of West Africa* (also in French, 70F)

No. 71 Mahmood, *Reservoir Sedimentation: Impact, Extent, and Mitigation*

No. 72 Jeffcoate and Saravanapavan, *The Reduction and Control of Unaccounted-for Water: Working Guidelines* (also in Spanish, 72S)

No. 73 Palange and Zavala, *Water Pollution Control: Guidelines for Project Planning and Financing* (also in Spanish, 73S)

No. 74 Hoban, *Evaluating Traffic Capacity and Improvements to Road Geometry*

No. 75 Noetstaller, *Small-Scale Mining: A Review of the Issues*

No. 76 Noetstaller, *Industrial Minerals: A Technical Review* (also in French, 76F)

No. 77 Gunnerson, *Wastewater Management for Coastal Cities: The Ocean Disposal Option*

No. 78 Heyneman and Fägerlind, *University Examinations and Standardized Testing: Principles, Experience, and Policy Options*

No. 79 Murphy and Marchant, *Monitoring and Evaluation in Extension Agencies* (also in French, 79F)

No. 80 Cernea, *Involuntary Resettlement in Development Projects: Policy Guidelines in World Bank–Financed Projects* (also in Spanish, 80S, and French, 80F)

No. 81 Barrett, *Urban Transport in West Africa*

No. 82 Vogel, *Cost Recovery in the Health Care Sector: Selected Country Studies in West Africa*

No. 83 Ewing and Chalk, *The Forest Industries Sector: An Operational Strategy for Developing Countries*

No. 84 Vergara and Brown, *The New Face of the World Petrochemical Sector: Implications for Developing Countries*

No. 85 Ernst & Whinney, *Proposals for Monitoring the Performance of Electric Utilities*

No. 86 Munasinghe, *Integrated National Energy Planning and Management: Methodology and Application to Sri Lanka*

No. 87 Baxter, Slade, and Howell, *Aid and Agricultural Extension: Evidence from the World Bank and Other Donors*

No. 88 Vuylsteke, *Techniques of Privatization of State-Owned Enterprises*, vol. I: *Methods and Implementation*

No. 89 Nankani, *Techniques of Privatization of State-Owned Enterprises*, vol. II: *Selected Country Case Studies*

No. 90 Candoy-Sekse, *Techniques of Privatization of State-Owned Enterprises*, vol. III: *Inventory of Country Experience and Reference Materials*

No. 91 Reij, Mulder, and Begemann, *Water Harvesting for Plant Production: A Comprehensive Review of the Literature*

No. 92 The Petroleum Finance Company, Ltd., *World Petroleum Markets: A Framework for Reliable Projection*

No. 93 Batstone, Smith, and Wilson, *The Safe Disposal of Hazardous Wastes: The Special Needs and Problems of Developing Countries*

No. 94 Le Moigne, Barghouti, and Plusquellec, *Technological and Institutional Innovation in Irrigation*

No. 95 Swanson and Wolde-Semait, *Africa's Public Enterprise Sector and Evidence of Reforms*

No. 96 Razavi, *The New Era of Petroleum Trading: Spot Oil, Spot-Related Contracts, and Futures Markets*

No. 97 Asia Technical Department and Europe, Middle East, and North Africa Technical Department, *Improving the Supply of Fertilizers to Developing Countries: A Summary of the World Bank's Experience*

No. 98 Moreno and Fallen Bailey, *Alternative Transport Fuels from Natural Gas*

(List continues on the inside back cover)

WORLD BANK TECHNICAL PAPER NUMBER 131

The Prospects for Agroforestry in the Tropics

P.K.R. Nair

The World Bank
Washington, D.C.

First printing November 1990

The complete backlist of publications from the World Bank is shown in the annual *Index of Publications*, which contains an alphabetical title list (with full ordering information) and indexes of subjects, authors, and countries and regions. The latest edition is available free of charge from the Publications Sales Unit, Department F, The World Bank, 1818 H Street, N.W., Washington, D.C. 20433, U.S.A., or from Publications, The World Bank, 66, avenue d'Iéna, 75116 Paris, France.

ISSN: 0253-7494

Library of Congress Cataloging-in-Publication Data

Nair, P.K.R.
The prospects for agroforestry in the tropics / P.K.R. Nair.
p. cm. — (World Bank technical paper, ISSN 0253-7494 ; no. 131)
Includes bibliographical references.
ISBN 0-8213-1702-4
1. Agroforestry—Tropics. 2. Agroforestry—Africa. I. Title. II. Series.
S494.5.A45N356 1990
634.9'9'0913—dc20 90-21204
CIP

Executive Summary

Agroforestry has come of age remarkably during the past 10 to 15 years. However, the lack of a synthesized 'package' of technical and socio-economic information on agroforestry is a serious drawback in channeling development assistance to agroforestry projects. The objective of this report is to fill this gap. By reviewing the scientific information currently available, the report seeks to establish the scientific basis and principles of agroforestry and to evaluate field research on agroforestry practices; it also discusses the economic and socio-cultural aspects of agroforestry, as seen by a 'non-expert'. A comprehensive bibliography is appended to the report.

The emphasis in this report is on Africa, but extensive use is also made of experiences from other parts of the developing world to ensure that the report is applicable to all tropical regions. It is addressed primarily to agroforestry practitioners — both foresters and agriculturalists — of the World Bank and similar development-support agencies. The major findings of this report are summarized here.

1. Agroforestry is widespread in almost all ecological and geographical regions of the tropics. The large number of agroforestry systems can be grouped according to certain structural and agro-ecological criteria. Although the socio-cultural aspects of these systems may vary from one geographical region to another, and the level of intensity with which the systems are managed may differ, those operating in areas with similar ecological conditions tend to have structural similarities, so that it is possible to identify a few distinct agroforestry practices that constitute the bulk of diverse agroforestry systems. The agro-ecological and structural analysis of agroforestry systems and practices provides a useful framework within which to develop approaches aimed at improving indigenous systems.

2. The oft-repeated suggestion that agroforestry holds considerable promise as a practical land-management alternative for maintaining soil fertility and productivity is based on the assumption that trees and other vegetation improve the soil beneath them. Trees add organic matter, nutrients and growth-promoting substances to soils, they help reduce soil loss from erosion, and they improve the physical and chemical properties of soils. However, they may also have some adverse effects on soils. The net effect of all these factors will depend upon management and location-specific factors.

3. Nitrogen-fixing trees are a most promising group of agroforestry components. Because they are able to fix atmospheric nitrogen and contribute nitrogen via leaf and litter fall and root turnover, they have a dominant role to play in maintaining soil fertility. Few direct measurements of nitrogen fixation by tropical trees have been made, but the literature does identify some species capable of fixing 50-100 kg N/ha per annum when grown in agroforestry systems. In terms of the nutrient requirements of crops, the potential of nutrient input through leaf litter could be considerable. Another important way in which trees improve soils is through nutrient cycling. Unlike nitrogen fixation, which is an input into the soil, nutrient cycling involves the turnover of nutrients already within the soil; this includes the translocation of nutrients from soil layers which are beyond the reach of annual crops or pasture species. There is also a growing recognition of the importance of roots in agroforestry systems, both as components of primary production and in soil-fertility maintenance. The challenge here is to maximize the

beneficial effects of root and mycorrhizal systems, whilst reducing tree-crop competition for moisture and nutrients. Clearly, there is a need for more knowledge about all the soil-related benefits of agroforestry.

4. The above-ground interactions between plants in mixed systems are usually viewed as competitive, but some complementary interactions have also been reported. There is scientific evidence to support the contention that photosynthetic efficiency may be greater in a mixed system, comprising structurally dissimilar components, than in a monocultural system. An obvious additional advantage is that mixed systems produce a greater variety of products than monocultural systems.

5. Although agroforestry research is constrained by unclear methodologies and the sheer multiplicity of factors to be taken into consideration, some promising research projects are under way in the tropics. Most of them concentrate on alley cropping (and other forms of hedgerow intercropping), and plantation crop combinations. A detailed examination of the rapidly growing amount of information on alley cropping shows that, on the relatively infertile alfisols in humid and subhumid regions, this practice helps maintain reasonable levels of soil fertility. It is a low-input practice, rather than a no-input practice; that is, to obtain the best results there must be some fertilizer input. In most cases, alley cropping allows crops to make more efficient use of fertilizers than is the case in monocropping systems. However, in the semi-arid tropics and other dry areas, alley cropping is unlikely to significantly improve soil fertility. In extremely acidic soils, the relevance and success of alley cropping depends on the extent to which inputs such as fertilizers are used. An additional constraint of alley cropping is the relatively high labor requirement. In general, it is clear that while some areas would benefit from alley cropping, others would not.

6. Where plantation crops are grown under monocultural systems, available solar energy and soil resources are not utilized to the fullest extent. By growing agricultural crops with plantation crops, greater use is made of these resources. Several shade-tolerant and economically useful plants can be grown between or under a plantation crop during different stages of its growth. Many of the plantation crop combination practices currently in use illustrate the potential of this form of agroforestry. However, the particular ecological requirements for the growth of plantation crops impose a limit on the use of these practices.

7. The environmental benefits of agroforestry, other than soil-related factors, include micro-climate amelioration. In many parts of the tropics there is widespread use of windbreaks and shelterbelts. Windbreaks can also provide other benefits, such as poles and fuelwood.

8. Although a large number of traditional agroforestry systems have been reported, only a few have been scientifically studied, and hence there is inadequate scientific understanding of such systems. The little research that has been done indicates the scientific merits of these time-tested systems and points to several possibilities for improving them.

9. Agroforestry is considered to be a sound and potentially promising strategy to address some of Africa's land-use problems. The use of an ecological approach could be a basis for developing appropriate agroforestry designs. Four broadly homogeneous ecozones can be demarcated for agroforestry development in sub-Saharan Africa: the upland plateau of southern Africa (unimodal); the highlands of eastern and central Africa (bimodal); the semi-arid lowlands (the Sahelian zone); and the humid lowlands of West Africa. This report suggests the broad agroforestry approaches that, with appropriate site-specific modification, could be applied in all regions, as well as specific approaches for each region. Two particular issues that are relevant throughout sub-Saharan Africa are: the integration of agriculture, forestry and wildlife

management through buffer-zone agroforestry; and the use of under-exploited food-producing trees and indigenous knowledge in agroforestry design.

10. Economic studies of agroforestry have been carried out on a rather ad hoc basis and are generally *ex ante* analyses, based on assumptions, rather than *ex post* analyses based on field data. This is mainly because of the dearth of experimental station and on-farm data. Moreover, in many studies the focus tends to be on the long-term economic benefits of the main components of agroforestry systems, with little documentation on short-term benefits and by-products. Nevertheless, the limited information that is available does provide some indication of the economic advantages and limitations of agroforestry in a variety of situations. Now that methodologies for economic analyses of agroforestry projects are becoming available, more detailed studies, based on field results, can be expected. Socio-cultural issues also need to be analyzed if new agroforestry technologies are to achieve wide acceptance by farming families.

Several important conclusions emerge from this review.

- Agroforestry systems are many and varied, as are their functions, roles and outputs.
- There is ample scientific evidence to indicate that the benefits to be derived from agroforestry could be considerably increased by appropriate scientific intervention.
- Scientific studies in agroforestry have been very limited, and thus the potential of agroforestry remains vastly under-exploited.
- The main scientific foundation of agroforestry is the multipurpose tree. The success of agroforestry will depend upon the extent to which the productive, protective and service potential of multipurpose trees is understood and exploited (through research) and realized (through development and extension efforts).
- The current trend in agroforestry development shows an imbalance between large-scale development projects and inadequately low levels of research and educational support.

Acknowledgements

The sources of tables, figures and other information used in this report are acknowledged in the text. Valuable comments and criticisms were provided by many distinguished professionals who reviewed a first draft of this document, including Emmanuel Asibey, Leif Christoffersen, Cynthia Cook, Keith Openshaw, Chip Rowe and John Spears (World Bank), Kenneth Fischer (IITA), Donald Kass (CATIE), Bjorn Lundgren (ICRAF), C. K. Ong and Tom Walker (ICRISAT) and Derrick Thomas (ILCA). Editorial assitance in preparing the final draft for publication was provided by Kay Sayce, of Chayce Publication Services.

The Author

Dr P. K. R. Nair is Professor of Agroforestry in theDepartment of Forestry, Institute of Food and Agricultural Sciences (IFAS), University of Florida, Gainesville, USA.

Contents

Introduction

Deforestation in the world's tropical regions is a major environmental issue. Estimates of the rates of deforestation vary widely, depending on the definitions of 'forest' and 'deforestation'. However, there is no divergence of opinion on the consequences of tropical deforestation — a decline in the productive capacity of soils, accelerated erosion, siltation of dams and reservoirs, destruction of wildlife habitats and loss of plant genetic diversity.

It is also generally agreed that the main causes of this deforestation are population resettlement schemes, forest clearance for large-scale agriculture, forestry enterprises and animal production, and, in particular, shifting cultivation. It is estimated that shifting cultivation is responsible for almost 70% of the deforestation in tropical Africa, and that forest fallows resulting from shifting cultivation practiced in recent times occupy an area equivalent to 26.5% of the remaining closed forest in Africa, 16% in Latin America, and 22.7% in tropical Asia (FAO, 1982).

Nevertheless, shifting cultivation remains the primary source of livelihood for millions of people in the tropics. As a land-use system, it has stood the test of time; only recently, largely because of population pressures, has it begun to break down. Attempts to replace shifting cultivation with large-scale mechanized farming for the production of seasonal crops have been largely unsuccessful, for both technical and socio-cultural reasons. The main technical reason is the inherent inability of the low-activity clay soils, predominant in most upland areas in the tropics and subtropics, to respond to large-scale mechanization and high levels of agrochemical inputs. Among the socio-cultural reasons are the incompatibility between the shifting cultivators' traditional social values and cultural outlook and the requirements of modern farming systems, and the lack of the institutional and infrastructural support necessary to initiate and sustain such massive changes. The complexity of the problem is compounded by the growing demand for fodder, fuelwood and timber, which all need to be produced from the same unit of land in a sustainable manner.

The emergence of agroforestry as a promising development strategy

Faced with this problem, tropical land-use experts and institutions intensified their search for appropriate land-use approaches that would be socially acceptable, ensure sustainability of the production base, and meet the need for production of multiple outputs. Foresters began designing major programs which would allow local communities to benefit directly from forests; these efforts paved the way for new concepts, such as social forestry. Building upon the success of scientific studies on multiple cropping, agronomists, soil scientists and horticulturists began investigating the feasibility of intercropping in tree-crop stands and studying the role of trees and shrubs in maintaining soil productivity and controlling soil erosion. Livestock management experts began to recognize the importance of indigenous tree-and-shrub browse in mixed farming and pastoral production systems. Ecologists produced convincing evidence of the positive influence of forests and trees on the stability of ecosystems. Environmental concern about the effects of deforestation grew, and the call for measures to protect the remaining forests and introduce more woody perennials into managed land-use systems intensified. Studies carried out by anthropologists and social scientists on farmer attitudes to improved land-use systems showed the importance of mixed systems in traditional cultures and highlighted the need to build upon these practices when developing new approaches.

The collective efforts of all these groups led inevitably to studies of age-old land-use practices based on tree-crop-livestock combinations on the same piece of land. It was soon realized, thanks mainly to the work of Bene et al. (1977), that these practices had the potential to alleviate some of the problems of tropical land management. Recognition of the inherent advantages of traditional land-use practices involving trees — sustained yield, environmental conservation and multiple outputs — grew considerably and, during the following decade, agroforestry came of age (Steppler and Nair, 1987).

There are many examples of low-input agroforestry systems in various ecological regions of the tropics where woody perennials are deliberately mixed with crops and/or animals in order to derive maximum economic and ecological benefit (Nair, 1989; Rocheleau et al., 1988). Although many of these systems have been little studied, there is now enough technical, sociological and economic information available to enable us to recommend the adoption of some of them (Steppler and Nair, 1987; MacDicken and Vergara, 1990; recent volumes of *Agroforestry Systems*). Indeed, in many areas of the tropics, the economic returns from agroforestry projects financed by the World Bank over the past decade have been significantly higher than those from the industrial forestry plantation projects that characterized earlier World Bank programs (Spears, 1987).

The role of the World Bank in promoting agroforestry

The World Bank's recognition of agroforestry as a promising development tool goes back to the late 1970s. In 1978, the Bank's Forestry Sector Review called attention to the need for increased funding for forestry, particularly for agroforestry research (World Bank, 1978). A decade later, in response to growing concern about the plight of the peoples of sub-Saharan Africa, the Bank conducted a comprehensive review of agricultural research activities in the region (Pickering, 1988). This review identified agroforestry as an appropriate and sustainable production system which could enhance land productivity and absorb the growing labor force. In 1989, a World Bank Symposium on agricultural extension services in Africa recommended that the development and transfer of suitable agroforestry 'packages' should become part of the responsibilities of extension services (Roberts, 1989).

A number of studies carried out by the World Bank, as well as by other development agencies such as the Food and Agriculture Organization of the United Nations (FAO, 1985), have indicated a high degree of social acceptability and adoption of agroforestry practices. Notable among these are the World Bank reports by Gregersen et al. (1988) and Cook and Grut (1989). The former examines ways of assisting governments in implementing social forestry programs, and underlines the need for a high level of local participation and strong political commitment to long-term solutions. The latter analyzes agroforestry from the farmers' perspective and provides useful guidelines for planning agroforestry projects in sub-Saharan Africa.

The need to synthesize available information on agroforestry

It is apparent from much of the information produced during the past decade that agroforestry has the potential to solve many of the land-use problems faced by farmers in tropical regions. However, this information is scattered in various formal and informal publications, and as yet there is no synthesized 'package' of information on agroforestry. This imposes limitations on channeling development assistance to agroforestry programs. The objective of this report is to fill this gap. It reviews the available technical, economic and socio-cultural information on agroforestry and assesses the potential of various agroforestry practices, particularly those which have been most studied, to address some of the land-use problems in the tropics. It does not attempt, however, to recommend the most appropriate agroforestry systems and practices for different parts of the world.

The emphasis in this report is on Africa, but extensive use is made of experiences from other areas and the report's conclusions are therefore applicable to all tropical regions in the developing world. The report is addressed mainly to agroforestry practitioners — both foresters and agriculturalists — of the World Bank and similar institutions, but it should also be useful to researchers involved in designing new or improved agroforestry systems and to field staff and others who are implementing agroforestry programs and projects in developing countries.

Chapter 1

Agroforestry Systems

DEFINITION AND CONCEPTS OF AGROFORESTRY

Following its conceptualization as a land-use approach in the late 1970s, there was a surge of enthusiasm to define agroforestry. As time passed, the definition proposed by the International Council for Research in Agroforestry (ICRAF) gained wide acceptance: 'Agroforestry is a collective name for land-use systems and technologies where woody perennials are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components.'

The key concepts of agroforestry are now well established, and it is generally accepted that agroforestry:

- is a collective name for land-use systems involving trees combined with crops and/or animals on the same unit of land;
- combines production of multiple outputs with protection of the resource base;
- places emphasis on the use of indigenous, multipurpose trees and shrubs;
- is particularly suitable for low-input conditions and fragile environments;
- is more concerned with socio-cultural values than most other land-use systems;
- is structurally and functionally more complex than monoculture.

TYPES OF TROPICAL AGROFORESTRY SYSTEMS

Between 1982 and 1987, ICRAF compiled an inventory of agroforestry systems and practices being used in the developing countries. The exercise, financed partly by the United States Agency for International Development (USAID), involved collecting, collating and evaluating data, and publishing the results. It brought together, for the first time, a substantial body of information on a large number of agroforestry systems, their structures and functions, and their merits and weaknesses (Nair, 1989). A summary of agroforestry systems in the tropics, based on this inventory, is given in Table 1. The most common types of systems in the tropics are listed in Table 2.

Table 1. Agroforestry systems in the tropics

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

Table I. (continued)

Subsystems and practices	South Pacific	South-East Asia	South Asia	Middle East and Mediterranean	East and Central Africa	West Africa	American Tropics
			SILVOPASTORAL SYSTEMS				
Protein bank (cut-and-carry) fodder production	Rare	Very common, especially in highlands	Multipurpose fodder trees on or around farmlands, especially in highlands		Very common	Very common	Very common
Live-fences of fodder trees and hedges	Occasional	*Leucaena, Calliandra* etc. used extensively	*Sesbania, Euphorbia, Syzigium*, etc. common		Very common in all ecological regions		Very common in highlands
Trees and shrubs on pasture	Cattle under coconut, pine and *Eucalyptus deglupta*	Grazing under coconut and other plantation crops	Several tree species being used very widely	Very common in dry regions; the Dehesa system	The *Acacia*-dominated system in the arid parts of Kenya, Somalia and Ethiopia	Cattle under oil-palm; cattle and sheep under coconut	Common in humid as well as dry regions e.g. grazing under plantation crops in Brazil
			AGROSILVOPASTORAL SYSTEMS				
Woody hedges for browse, mulch, green manure, soil conservation etc.	Various forms; *Casuarina oligodon* widely used to provide mulch and compost	Various forms	Various forms, especially in lowlands		Common; variants of the Shamba system	Very common	Especially in hilly regions
Homegardens (involving a large number of herbaceous and woody plants and/or livestock)	Several types of homegardens and kitchen gardens	Very common; Java homegardens often quoted as good examples; involving several fruit trees	Common in all ecological regions; usually involving fruit trees	The oasis system	Various forms; the Chagga homegardens; the Nyabisindu system	Compound farms in humid lowlands	Very common in thickly populated areas
			OTHER SYSTEMS				
Agrosilvo fishery (aquaforestry)		Silviculture in mangrove areas; trees on bunds of fish-breeding ponds	Occasional				
Various forms of shifting cultivation	Common	Swidden farming and other forms	Very common; various names		Very common	Very common in the lowlands	Very common in all ecological regions
Apiculture with trees	Common	Common	Common	Common	Common	Common	

Source: Nair (1989)

Table 2. Common agroforestry systems in the tropics

HUMID LOWLANDS	SEMI-ARID LOWLANDS	HIGHLANDS
Shifting cultivation	Silvopastoral systems	Soil consevation hedges
Taungya	Windbreaks/shelterbelts	Silvopastoral combinations
Homegardens	Multipurpose trees for fuel/fodder	Plantation crop systems
Plantation crop combinations	Multipurpose trees for farmlands	
Multilayer tree gardens		
Intercropping systems		

As Table 1 shows, agroforestry is practiced in almost all ecological regions of the tropics and the types of systems used are diverse and complex. In order to evaluate these systems and develop plans of action to improve them, it is necessary to classify them. The most commonly used criteria used to classify agroforestry systems are structure (composition and arrangement of components), functions, socio-economic scale of management, and ecological spread. However, as all systems are characterized by three basic components — woody perennials (trees), herbaceous plants (crops) and animals — a logical first step is to classify them according to their component composition. As shown in Figure 1, there are three basic types of agroforestry systems:

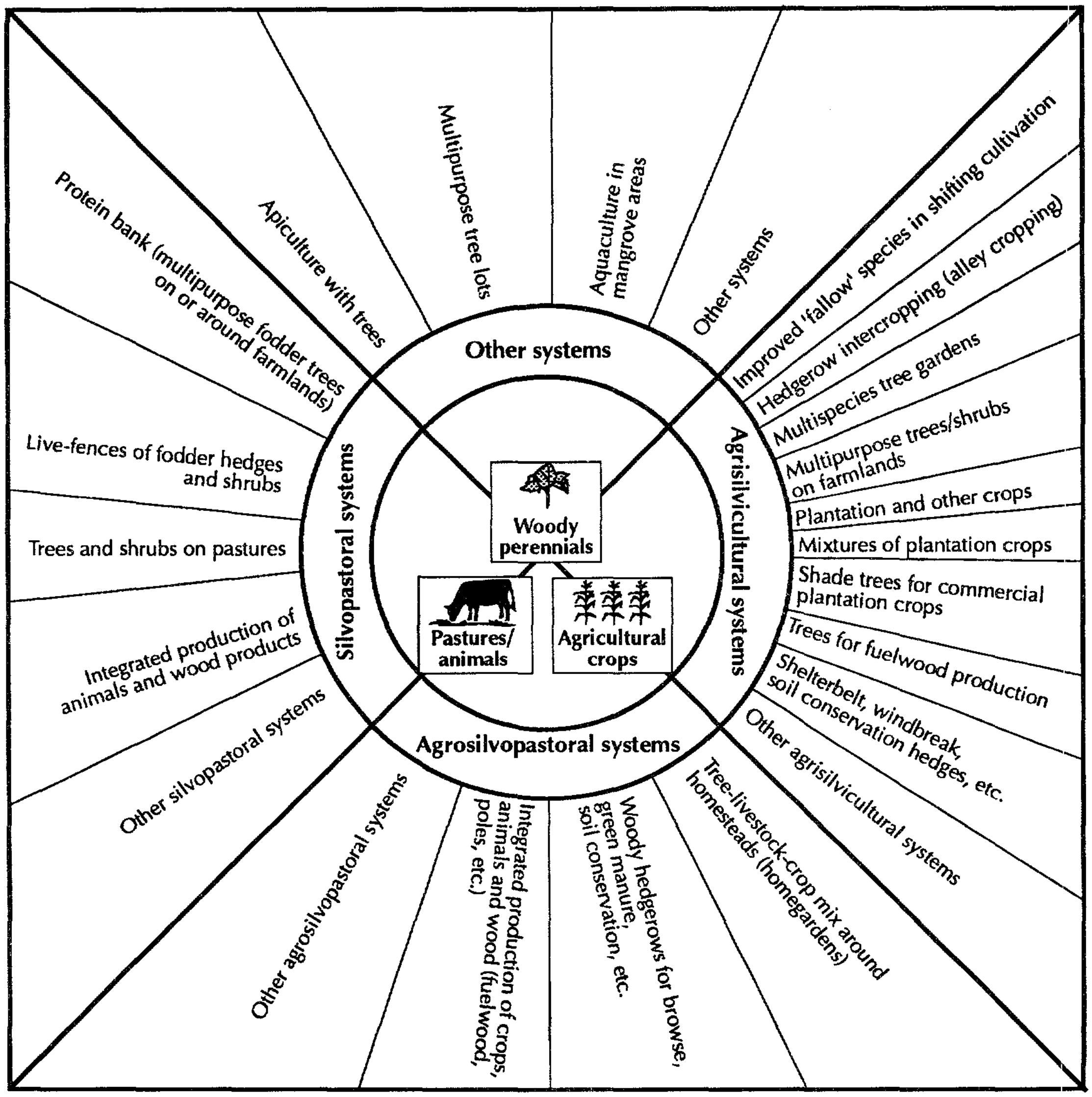
- agrisilvicultural (crops and trees)
- silvopastoral (trees and pasture/animals)
- agrosilvopastoral (crops, trees and asture/animals)

Other specialized agroforestry systems can also be defined (for example, apiculture with trees, aquaculture involving trees and shrubs, and multipurpose-tree lots).

In any one agroforestry system there can be more than one agroforestry *practice*. An agroforestry system is characterized by certain types of practices that, taken as a whole, form a dominant land-use system in a particular locality and determine its overall biological composition and arrangement. An agroforestry practice, on the other hand, denotes a specific land-management unit, such as a field, and a specific arrangement, temporally and/or spatially, of components. Although several types of agroforesty systems have been recorded, the number of distinct practices is small. In other words, the same or similar practices are found in various systems in different parts of the tropics. Table 3 gives the main characteristics of the most common practices in the tropics.

The scale of management and extent of adoption of different agroforestry practices in a given system varies considerably. Any one of these practices can be developed in a particular area to the point where it forms a distinct type of land use in that area and thus becomes an agroforestry system. One essential point to note here is that an agroforestry practice can be found in a non-agroforestry land-use system. An example of this is the practice of growing rows of *Sesbania grandiflora* on the bunds of rice paddies in Java, Indonesia. The leaves of this woody species are used as green manure, its flowers are eaten as a vegetable and its wood is used as fuel; in addition, through biological fixation of atmospheric nitrogen, it improves the fertility of the soil. However, although it is interacting ecologically and economically with the rice crop, it is not the predominant land-use practice but simply an agroforestry practice in a crop production system.

Figure 1. Classification of agroforestry systems based on the type of components



Source: Nair (1985)

Most, if not all, of the practices listed in Table 3 need to be improved scientifically and developed into modern agroforestry technologies. The success of an agroforestry practice (and therefore system) depends on the extent to which such technologies have been perfected and the degree to which they are used in the management of the practice (or the system). The term 'agroforestry technology' is used here to refer to an innovation or improvement, usually through scientific intervention, that can be applied with advantage in the management of an agroforestry system or practice. The inputs used to develop a new technology, such as improved varieties and agrochemicals, are referred to as input technologies and are often the most important part of a new technology.

Table 3. Main characteristics of the most common agroforestry practices in the tropics

Agroforestry practice	Brief description of arrangement of components	Major groups of components	Agro-ecological adaptability
		AGRISILVICULTURAL SYSTEMS (crops — including shrub/vine/tree crops — and trees)	
Improved fallow	Woody species planted and left to grow during the 'fallow phase'	w fast-growing preferably leguminous h common agricultural crops	In shifting cultivation areas
Taungya	Combined stand of woody and agricultural species during early stages of establishment of plantations	w usually plantation forestry species h common agricultural crops	All ecological regions, where taungya is practised; several improvements possible
Alley cropping (hedgerow intercropping)	Woody species in hedges; agricultural species in alleys in between hedges; microzonal or strip arrangement	w fast-growing, leguminous species that coppice vigorously h common agricultural crops	Subhumid to humid areas with high human population pressure and fragile (productive but easily degradable) soils
Multilayer tree gardens	Multispecies, multilayer dense plant associations with no organized planting arrangements	w different woody components of varying forms and growth habits h usually absent; shade-tolerant ones sometimes present	Areas with fertile soils, good availability of labor, and high human population pressure
Multipurpose trees on croplands	Trees scattered haphazardly or according to some systematic patterns on bunds, terraces or plot/field boundaries	w multipurpose trees and other fruit trees h common agricultural crops	In all ecological regions, especially in subsistence farming; also commonly integrated with animals
Plantation crop combinations	1. Integrated dense multistorey mixtures of plantation crops 2. Mixtures of plantation crops in alternate or other regular arrangements 3. Shade trees for plantation crops; shade trees scattered 4. Intercropping with agricultural crops	w plantation crops such as coffee, cacao, coconut and fruit trees (especially in 1); fuelwood/fodder species (especially in 3) h usually present in 4, and to some extent in 1; shade-tolerant species	In humid lowlands or tropical humid/subhumid highlands (depending on the plantation crops concerned); usually in smallholder subsistence systems
Homegardens	Intimate, multistorey combination of various trees and crops around homesteads	w fruit trees predominate; also other woody species, vines, etc.	In all ecological regions, especially in areas of high population density
Trees in soil conservation and reclamation	Trees on bunds, terraces, raisers, etc., with or without grass strips; trees for soil reclamation	w multipurpose and/or fruit trees h common agricultural species	In sloping areas, especially in highlands, reclamation of degraded, acid, alkali soils, and sand-dune stabilization
Windbreaks and shelterbelts, live-hedges	Trees around farmlands/plots	w combination of tall-growing spreading types h local agricultural crops	In wind-prone areas
Fuelwood production	Interplanting fuelwood species on or around agricultural lands	w fuelwood species h local agricultural crops	In all ecological regions

Table 3. (continued)

Agroforestry practice	Brief description of arrangement of components	Major groups of components	Agro-ecological adaptability
		SILVOPASTORAL SYSTEMS (trees and pastures and/or animals)	
Trees on rangeland or pastures	Trees scattered irregularly or arranged according to some systematic pattern	w multipurpose; of fodder value f present a present	Extensive grazing areas
Protein banks	Production of protein-rich tree fodder on farm/rangelands for cut-and-carry fodder production	w leguminous fodder trees h present f present	Usually in fairly densely populated areas
Plantation crops with pastures and animals	Example: cattle under coconut crops in south-east Asia and south Pacific	w plantation crops f present a present	In areas with less pressure on plantation crops
		AGROSILVOPASTORAL SYSTEMS (trees and crops and pasture/animals)	
Homegardens with animals	Intimate, multistorey combination of various trees and crops, as well as animals around homesteads	w fruit trees predominate; also other woody species a present	In all ecological regions with high human population density
Multipurpose woody hedgerows	Woody hedges for browse, mulch, green manure, soil conservation, etc.	w fast-growing and coppicing fodder shrubs and trees h similar to alley cropping and soil conservation	Humid to subhumid areas with hilly and sloping terrain
		OTHERS	
Apiculture with trees	Trees for honey production	w honey producing (other components may be present)	Depending on the feasibility of apiculture
Aquaforestry	Trees lining fish ponds, tree leaves being used as 'forage' for fish	w trees and shrubs preferred by fish (other components may be present)	Lowlands
Multipurpose woodlots	For various purposes (wood, fodder, soil protection, soil reclamation, etc.)	w multipurpose species; location-specific species (other components may be present)	Various

Note: w = woody, h = herbaceous, f = fodder, a = animals

AGROECOLOGICAL ANALYSIS OF TROPICAL AGROFORESTRY SYSTEMS

The type of agroforestry system found in a particular area is determined to some extent by agro-ecological factors. However, several socio-economic factors, such as human population pressure, availability of labor and proximity to markets, also come into play, resulting in considerable variations among systems operating in similar or identical agro-climatic conditions. Sometimes, socio-economic factors take precedence over ecological considerations. Even in the case of systems that are found in most ecological and geographical regions, such as shifting cultivation and taungya, there are numerous variants that are specific to certain socio-economic contexts. As a general rule, it can be said that while ecological factors determine the major type of agroforestry system in a given area, the complexity of the system and the intensity with which it is managed increase in direct proportion to the population intensity and land productivity of the area.

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

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

The ecological and geographical distribution of the major agroforestry systems in the world has been schematically presented by Nair (1989). However, caution must be exercised in producing and interpreting such 'agroforestry maps' because they aim to show general distribution patterns and thus include only those areas in which specified agroforestry systems are abundant. There are innumerable location-specific agroforestry practices in the tropics which, although important in certain respects, are not significant enough in terms of the overall economy and land-use pattern of the area in which they operate to warrant inclusion on a global map. Conversely, some practices, such as 'multipurpose trees on farmlands', are found in almost all ecological and geographical regions, but only a few of them — for example, the arid zone systems involving *Acacia* (*Faidherbia*) *albida* (Miehe, 1986; Poschen, 1986) and *Prosopis* (Shankarnarayan et al., 1987) — can be classified as distinct agroforestry systems and included on an agroforestry map.

A significant feature that emerges from this type of ecological and geographical analysis of tropical agroforestry systems is that, irrespective of the socio-cultural differences in different geographical regions, the major types of agroforestry systems are structurally similar in areas with similar or identical ecological conditions.

Chapter 2

Scientific Basis of Agroforestry

The most distinctive element of agroforestry is the multipurpose tree (or multipurpose trees and shrubs). It has been said, rightly, that 'all trees are multipurpose, but some are more multipurpose than others'. In agroforestry, the emphasis is on the multipurpose nature of trees, whereas in forestry trees tend to be perceived as 'monopurpose' plants. The perception of trees as multipurpose plants is based on their productive attributes (for example, food, fodder, fuelwood and small timber) and their protective or service functions (in relation, for example, to soil conservation and soil fertility improvement).

These attributes and functions form the scientific basis of agroforestry, and should therefore be the basis of a scientific analysis of the subject. However, although it is relatively easy to quantify the productive attributes, it is far more difficult to evaluate the protective and service functions. The first part of this chapter assesses agroforestry in terms of its contribution to soil fertility and productivity.

The performance of any multipurpose tree is determined not only by its inherent attributes, but also by the conditions under which it grows. A fundamental criterion for evaluating the success of any multiple cropping and multiple-enterprise system, including agroforestry, is the overall performance of the system as a whole, rather than that of its individual components. Thus, although multipurpose trees are the foundation of all agroforestry systems, it is important to examine their interaction with other components of these systems. The second part of this chapter, therefore, assesses the productivity of mixed plant communities.

SOIL FERTILITY AND PRODUCTIVITY

It is now widely believed that agroforestry holds considerable potential as a major land-management alternative for conserving the soil and maintaining soil fertility and productivity in the tropics. This belief is based on the assumption that trees and other vegetation improve the soil beneath them. Observations of interactions in natural ecosystems have identified a number of points which support this assumption:

- from time immemorial, farmers have known that they will get a good crop by planting in forest clearances;
- soils that develop under natural woodland and forest are known to be well structured, with good moisture-holding capacity and high organic matter content;

- unlike agricultural systems, a forest ecosystem is a closed system in terms of nutrient transfer, storage and cycling;
- the ability of trees to restore soil fertility is illustrated by experiences in many developing countries, notably India, which indicate that the best way to reclaim degraded land is through afforestation or a similar type of tree-based land use;
- the conversion of natural ecosystems to arable farming systems leads to a decline in soil fertility and a degradation of other soil properties unless appropriate, and often expensive, corrective measures are taken;
- the microsite enrichment qualities of trees such as *Acacia (Faidherbia) albida* in West Africa (Felker, 1978) and *Prosopis cineraria* in India (Mann and Saxena, 1980) have long been recognized in many traditional farming systems.

These observations have led to a number of studies on the role of trees in soil productivity and protection, especially in the context of agroforestry development. Notable among these reviews are those by Nair (1984, 1987) on soil productivity and management issues in agroforestry, by Wiersum (1986) and Lundgren and Nair (1985) on the role of agroforestry in soil conservation, and by Young (1989) on agroforestry as a practical means of sustaining soil fertility. Several investigations have been carried out on the soil fertility aspects of particular tree-based systems, including alley cropping (Kang and Wilson, 1987; Sanchez, 1987; Juo, 1989; Kang et al., 1989; Avery et al., 1990). It has been suggested that the presence of trees will lead to an improvement in soil water supplies (Nair, 1984, 1987; Young, 1988), but this issue has not been studied in the context of agroforestry and therefore is not reviewed here.

It is clear from the following discussion that a substantial volume of scientific information on the soil-improving attributes of trees is being built up, and there is now more than enough evidence to indicate that trees and shrubs, if managed properly, can make a significant contribution to maintaining and improving the fertility and overall productivity of the soil beneath them.

Effect of Trees on Soils

Drawing on evidence from current land-use systems involving trees, Nair (1984, 1987) put forward some hypotheses on the beneficial effects on soils of tree-based systems in general, and agroforestry in particular (*see* Table 4). These have since been amplified by Sanchez (1987) and Young (1989). The following outline of the effects of trees on soils is based largely on Young's review.

Beneficial effects

Additions to the soil

- *Maintenance or increase of organic matter:* This has been proven and widely demonstrated, and is quantitatively known through studies of organic matter cycling under natural forest.
- *Nitrogen fixation:* This has been proven, both indirectly through soil nitrogen balance studies and directly by observation of nodulation and tracer studies.
- *Nutrient uptake:* This is probable, but has not been demonstrated. The hypothesis is that, in general, trees are more efficient than herbaceous plants in taking up nutrients released by the weathering of deeper soil horizons. Potassium, phosphorus, bases and micronutrients are released by rock weathering, particularly in the B/C and C soil horizons which tree roots often penetrate.

Table 4. Beneficial effects of trees on the soil

Nature of process	Process	Main effect on soil	Scientific evidence
Input processes (augment additions to the soil)	Biomass production	Additions of carbon and its transformations	Available
	Nitrogen fixation	Nitrogen enrichment	Available
	Rainfall	Effect on rainfall (quantity and distribution) and therefore nutrient addition through rain	Not adequately demonstrated
Output process (reduce losses from the soil)	Protection against water and wind erosion	Reduced loss of soil and nutrients	Available
Turn-over processes	Nutrient retrieval/ cycling/release	Uptake from deeper layers and 'deposition' on surface via litter	Not adequately demonstrated
		Withholding nutrients that can be lost by leaching	Not demonstrated
		Timing of nutrient release which can be regulated by management interventions	Available
'Catalytic' processes (indirect influences)	Physical processes	Improvement of physical properties (water-holding capacity, permeability, drainage, etc.) at the microsite as well as at watershed (macrosite)	Available
	Root growth and proliferation (enhanced)	Addition of (more) root biomass; growth-promoting substances; microbial associations	Partially demonstrated
	Litter quality and dynamics	Improvement of litter quality through diversity of plant species; better timing of quantity, and method of application of litter possible	Now being increasingly studied (alley cropping and other intercropping experiments)
	Microclimatic processes	Creation of more favorable microclimate; shelterbelt and windbreak effects	Available
	(Bio)chemical/ biological processes (net effects of various processes)	Moderating effect on extreme conditions of soil acidity, alkalinity, etc.	Partially demonstrated

Source: Nair (1987)

- *Atmospheric input:* Atmospheric deposition makes a significant contribution to nutrient cycling, more so in humid regions than in dry regions. It consists of nutrients dissolved in rainfall (wet deposition) and those contained in dust (dry deposition). Trees reduce wind speed considerably and thus provide favorable conditions for dry deposition.

- *Exudation of growth-promoting substances into the rhizosphere:* This has been suggested but not demonstrated. Specialized biochemical studies would be required to demonstrate the presence and magnitude of any such effect, and to separate it from other influences of roots on plant growth.

Reduction of losses from the soil

- *Protection from erosion:* The most serious effect of erosion is loss of soil organic matter and nutrients, and the resulting reduction in crop yield. Forest cover reduces erosion to low levels, primarily through ground-surface litter cover and understorey vegetation; the protection afforded by the tree canopy is relatively slight.

- *Nutrient retrieval:* It is commonly supposed that tree root systems intercept, absorb and recycle nutrients in the soil that would otherwise be lost through leaching, thereby making a more closed nutrient cycle. The mycorrhizal systems associated with the tree roots are an agent in this process; they penetrate a large proportion of the soil, facilitating the uptake of nutrients which can move only short distances by diffusion. Evidence for this mechanism comes from the relatively closed nutrient cycles found under forest. The efficiency of mycorrhiza is demonstrated by the sometimes dramatic effects of mycorrhizal inoculation on plant growth (Atkinson et al., 1983; ILCA, 1986).

Effect on physical properties of the soil

- *Maintenance or improvement of physical properties:* The enhancement of such properties as soil structure, porosity, moisture retention and erosion resistance under forest is well documented, as is the decline of these properties in forest clearance. Porosity is a key to many other physical properties: pores 5-50 μm diameter determine available water-holding capacity, while those over 250 μm are necessary for root penetration. There is much evidence of the influence of physical properties of tropical soils on crop growth, independent of nutrient or other effects (Lal and Greenland, 1979).

- *Modification of extremes of soil temperature:* Studies of minimum tillage show that high soil temperatures adversely affect crop growth and that ground-surface litter cover greatly reduces the high ground-surface temperatures of bare soils in the tropics; these temperatures sometimes exceed 50°C (Harrison-Murray and Lal, 1979). It is likely that leaf litter cover produced by trees would have a similar effect.

Effect on chemical properties of the soil

- *Reduction of acidity:* Trees tend to moderate the effects of leaching through the addition of bases to the soil surface. However, it is doubtful whether tree litter plays a significant part in raising pH on acid soils, except through the release of bases built up during many years of tree growth, as in forest clearance or the *chitemene* system of shifting cultivation in northern Zambia.

- *Reduction of salinity or sodicity:* Afforestation has been used successfully to reclaim saline and alkaline soils. For example, under *Acacia nilotica* and *Eucalyptus tereticornis* in the Karnal region in India, a reduction of topsoil pH from 10.5 to 9.5 over five years and of electrical conductivity from 4 to 2 dS/m has been reported, but with tree establishment assisted by additions of gypsum and manure (Gill and Abrol, 1986; Grewal and Abrol, 1986 Singh et al., 1988). In this type of reclamation, the improvement in the soil's chemical properties undoubtedly results partly from improved drainage (ditches), which leads to better leaching.

- *Effects of shading:* Shade lowers ground-surface temperatures, which may reduce the rate of loss of soil organic matter by oxidation. Estimates of the humus decomposition constant are higher for agriculture than for woody fallows, although this may be primarily because of greater aeration of soil under cultivation.

Adverse effects

Trees, both as individual plants and when grown in association with herbaceous plants, can have adverse effects on soils. The main soil-related problems are given here; they do not include shading because this problem concerns the tree/crop interface rather than soils.

- *Loss of organic matter and nutrients in tree harvest:* A major concern in forestry is the depletion of soil resources by fast-growing trees, and the effect of this on subsequent forest rotations. Trees accumulate large quantities of nutrients in their biomass, part of which is removed in harvest. The problem is greatest where there is whole-tree harvesting (for example, the gathering of fine branches and litter by local people after a timber harvest). From a soil management point of view, it is desirable to allow all branches and litter to decay *in situ* and even to return bark, but this often conflicts with the needs of the local people, to whom such a practice appears unreasonable.
- *Nutrient competition between trees and crops:* This problem is most likely to be serious when trees or shrubs have an established root system that dominates that of newly planted annual crops. The rooting systems of trees in agroforestry systems should have deep penetration but limited lateral spread. Whereas lateral spread of the canopy can be controlled by pruning, root pruning is generally too expensive to be practicable.
- *Moisture competition between trees and crops:* In the semi-arid and dry savanna zones, this is possibly the most serious problem encountered in agroforestry.
- *Production of substances which inhibit germination or growth:* Some *Eucalyptus* species produce toxins which can inhibit the germination or growth of some annual herbs (Poore and Fries, 1985). It has also been suggested that the production of allelopathic substances by tree roots could present a problem in agroforestry, but there is little evidence of this.

In summary, where the growth of crops or pastures located near or beneath trees is inhibited, it is important to establish the degree to which this is caused by one or more of the above factors.

Most of the beneficial and adverse effects of trees on soils mentioned here are either inferred from tree-based land-use systems or are still only untested hypotheses. The degree to which they are significant in a given locality will depend upon certain site-specific factors. Moreover, many of the attributes of trees, as compared to annual crops, can be assessed only over relatively long periods.

Nitrogen-Fixing Trees

Nitrogen-fixing trees are among the most promising components of agroforestry systems. Because of their ability to fix atmospheric nitrogen and contribute nitrogen to the soil via leaf litter and the turnover/decomposition of root debris and nodules, they have a dominant role to play in maintaining soil fertility in agroforestry systems.

Biological nitrogen fixation takes place through symbiotic and non-symbiotic means. Symbiotic fixation occurs through the association of plant roots with nitrogen-fixing micro-organisms. Many legumes are associated with the bacteria *Rhizobium*; a few non-leguminous species are associated with the actinomycetes, *Frankia*. Non-symbiotic fixation is effected by free-living soil organisms, and can be a significant factor in natural ecosystems, with their relatively modest requirements, but is of minor importance in agricultural systems, which impose far greater demands on soils. Presumably, it varies according to the organic content, and therefore the microbiological activity, of the soil.

Nitrogen fixation by herbaceous legumes has long been exploited in agriculture, by growing nitrogen-fixing species as a productive crop (for example, pulses and groundnuts), as a green manure crop (for example, *Stylosanthes* species and *Centrosema pubescens*) or as a cover crop in perennial plantations (for example, *Pueraria phaseoloides*). Nitrogen-fixation rates for most herbaceous legumes are in the range of 40 to 200 kg N/ha/yr (Nutman, 1976; LaRue and Patterson, 1981; Gibson et al., 1982).

Measuring nitrogen fixation

There have been few direct measurements of nitrogen fixation by tropical trees, mainly because all three methods of measurement — acetylene reduction, nitrogen difference and ^{15}N labeling — are difficult to use (Roskoski, 1986; Dommergues, 1987).

In a plantation of *Leucaena leucocephala* in Tanzania, Hogberg and Kvarnstrom (1982) measured the instantaneous rates of acetylene reduction to ethylene, and used approximate extrapolation and conversion factors to arrive at an N fixation figure of 110 kg/ha/yr. Acetylene reduction measurements carried out by Roskoski (1981) in a Mexican coffee plantation indicated that whereas *Inga jinicuil* fixed over 40 kg N/ha/yr, a negligible amount was fixed by *I. vera.* Because this technique is an instantaneous measurement of relative nitrogenase activity, it requires calibration of acetylene reduction rates against direct measures of nitrogen fixation and must take into account variations in activity with nodule biomass, soil nutrients, and time of day and season (Roskoski, 1981; van Kessel and Roskoski, 1981; Roskoski and van Kessel, 1985).

Using the difference method in a study in Nigeria, Sanginga et al. (1986) estimated that *Leucaena leucocephala* fixed 224-274 kg N/ha in 24 weeks. However, the addition of 150 kg N/ha in fertilizer led to an increase of 271 kg N/ha in non-nodulated trees, implying that the reference plants were so severely nitrogen-stressed that the difference estimates were suspect. In a more recent study of *L. leucocephala*, growing on alfisols at the International Institute of Tropical Agriculture (IITA), near Ibadan in Nigeria, Sanginga et al. (1989) showed that fixation was 76-133 kg N/ha in six months when estimated by the difference method, and 98-134 kg N/ha in six months using the ^{15}N dilution method. The study also showed that the application of nitrogen fertilizer reduced the amount of nitrogen fixed by the plants and that, when inoculated with *Rhizobium*, *L. leucocephala* derived about 5% of its nitrogen from applied fertilizer and about 55% from the soil.

Using difference and ^{15}N dilution methods, Gauthier et al. (1985) estimated that fixation by *Casuarina equisetifolia*, grown in 1 m^3 containers, was the equivalent of 40-60 kg N/ha/yr. These methods were also used by Ndoye and Dreyfus (1988) in their study on *Sesbania rostrata* and *S. sesban*. The former fixed 45-51% of its nitrogen under flooded conditions and 35-36% in well-drained soil; the respective figures for *S. sesban* were 11-13% and 18%.

Table 5 summarizes the reported rates of nitrogen fixation by trees and shrubs. Because of the short-comings of nitrogen-fixation measurement methods, these are very approximate. Most data refer to the tree in a pure stand, but the data for coffee with *Inga* species and alley cropping with *Leucaena leucocephala* refer to spatially mixed and zoned agroforestry systems, respectively. The range is large,

Table 5. Nitrogen fixation by trees and shrubs

Species	Nitrogen fixation (kg N/ha/yr)	Source
Acacia (Faidherbia) albida	20	Nair (1984)
Acacia mearnsii	200	Dommergues (1987)
Allocasuarina littoralis	220 (?)	Dommergues (1987)
Casuarina equisetifolia	60-110	Dommergues (1987)
Coffee and *Inga* spp.	35	Roskoski and van Kessel (1985)
Coriaria arborea	190	Dommergues (1987)
Erythrina poeppigiana	60	Dommergues (1987)
Gliricidia sepium	13	Dommergues (1987)
Inga jinicuil	35-40	Dommergues (1987)
Inga jinicuil	50	Roskoski (1982)
Inga jinicuil	35	Roskoski and van Kessel (1985)
Leucaena leucocephala	100-500	Dommergues (1987)
Leucaena leucocephala	75-120	Mulongoy (1986)
Leucaena leucocephala (in hedgerow intercropping)	100-130 (6 months)	Sanginga et al. (1987)
Prosopis glandulosa	25-30	Rundel et al. (1982)
Prosopis glandulosa	40-50	Virginia (1986)
Prosopis tamarugo	200	Nair (1984)
Rain forest fallow	40-100	Greenland (1985)
Mature rain forest	16	Jordan et al. (1982)

Note: Nair (1984) and Dommergues (1987) are compilations from primary sources
Source: Young (1989)

from 20 to 200 kg N/ha/yr; only *L. leucephala* is capable of higher values under favorable climatic and soil conditions. There is a need for more data, but it is at least possible to identify trees and shrubs which, when grown in agroforestry systems, are capable of fixing 50-100 kg N/ha/yr.

The role of nitrogen-fixing trees in agroforestry

Nair (1988) examined the nitrogen-fixing trees in Asian farming systems and observed that several of them are already important components of these systems, providing a variety of services and benefits (*see* Table 6). Similar observations have been made in other parts of the tropics. In his review of the role of nitrogen-fixing trees in agroforestry, Dommergues (1987) concluded that the direct and indirect benefits from these trees vary greatly according to species, climate, soil and management practices.

Although a large number of nitrogen-fixing trees have been identified in various indigenous agroforestry systems (Brewbaker, 1987a; Nair, 1988, 1989), only a few of them have received serious research attention. These include *Leucaena leucocephala* (Brewbaker, 1987b; *Leucaena* Research Reports), *Gliricidia sepium* (Withington et al., 1987), *Sesbania* species (Evans and Rotar, 1987; ICRAF/NFTA, 1989), *Acacia (Faidherbia) albida* (Felker, 1978), and *Prosopis* species (Felker, 1986). However, awareness of the importance of nitrogen-fixing trees has increased considerably recently, thanks largely to the efforts of the Nitrogen-Fixing Tree Association (NFTA), and this bodes well for future research in this area. Based in Hawaii, but with a global network and a strong publications program, the NFTA has now progressed from listing nitrogen-fixing species in indigenous agroforestry systems and describing their characteristics to conducting research on nitrogen-fixation

Table 6. Perennial legumes commonly used in Asian farming systems

Species	Ecological adaptation	Growth form and characteristics	Major uses or functions [1]	N^2 fixation capability [2]	Other remarks
Acacia (Faidherbia) albida	Dry zones, drought-tolerant	Tree to 20 m, thorny	F,GM, A, SF, WLR	+	Leafless in rainy season, common in African systems
Acacia suriculiformis	Lowland humid tropics	Tree to 20 m	PW, Or, SC, FW, ST	+	Pulpwood species
Acacia mangium	Lowland humid to subhumid	Tree to 20 m	FW, SC, T, PW, SB	+	Plantation species, fast growing
Acacia nilotica	Dry zones, drought-tolerant	Tree to 10 m, very thorny, deciduous	SC, FW, T, A, DS, WLR,	+	Widespread in dry areas
Acacia polycantha (A. catechu)	Lowlands, low drought tolerance	Tree to 25m, coppices well	A, FW, G	+	Good fodder
Acacia saligna (A. cyanophylla)	Dry zones, lowlands and midlands, tolerant of salt and drought	Tree to 10 m, fast growing, shrubby	FW, T, DS, WLR	+	
Acacia senegal	Dry zones, lowlands and midlands	Tree to 10 m, thorny, deciduous, shrubby	FW, WLR, DS, G	+	Gum-arabic tree
Acacia seyal	Dry zones	Slender tree to 12 m, long thorns	A, G, T, WLR	+	Important animal feed
Acacia tortilis	Dry (arid) zones, tolerant of alkalinity and drought	Flat-topped tree to 15 m, thorny	FW, A, WLR	+	More popular in Africa
Acacia xanthophloes	Dry to subhumid tropics	Tree to 20 m, spiny	O, Or, FW	+	Lopped fodder
Albizia chinensis	Up to 1500m, dry to subhumid subtropics	Tree to 15 m, deciduous, fast growing	T, A, ST	+	Rapid growth
Albizia falcataria	Humid to submid lowlands	Tree to 30 m	SF, PW, Or	+	Common in south-east Asia as a plantation species
Albizia lebbek	Wide adaptability, dry to humid tropics	Tree to 25 m	FW, A, CT, Or	+	Rapid growth
Albizia odoratissima	Tropical highlands	Tree to 25 m	A, Or	+	Highly lopped for fodder
Cajanus cajan	Wide adaptability	Annual to perennial	F, GM, FW, SC, A	+	Widely used for a variety of purposes
Calliandra calothyrsus	Humid tropical midlands, acid-tolerant	Shrub to 8 m, fast growing	FW, SC, BF, GM, A, Or, T	+	Low fodder value
Cassia siamea	Semi-arid to subhumid, drought-tolerant	Shrub to 8 m, coppices vigorously	FW, SC, FW, A	-	Good for alley cropping

Table 6. (continued)

Species	Ecological adaptation	Growth form and characteristics	Major uses or functions [1]	N^2 fixation capability [2]	Other remarks
Dalbergia sissoo	Tropical and subtropical midlands, subhumid to humid	Tree to 30 m	T, FM, ST, A	+	Indian teakwood
Erythrina spp.	Humid lowlands to highlands	Tree to 20 m, often thorny, coppices well, propagated by stem cuttings	GM, ST, Or, WB, A	+	Used as live standard for black pepper
Flemingia macrophylla	Humid lowlands	Shrub to 3 m	GM, A	+	Common in south-east Asia as a green manure crop in plantations
Gliricidia sepium	Humid to subhumid lowland tropics	Tree to 20 m, vigorous coppicing fast growing	GM, A, FW, ST, SC	+	Very commonly used multipurpose species
Hardwickia binata	Dry tropics, drought-tolerant	Tree to 30 m, slow growing	W, SC, A, FW DS, Fi	0	Valued heavy wood
Leucaena leucocephala	Humid to subhumid lowlands, not acid-tolerant	Tree to 20 m, vigorous coppicing, fast growing	GM, A, FW, ST, SC, PW, F	+	Widely studied and extensively used
Pithecellobium dulce	Wide adaptability from dry to humid zones	Tree to 20 m, thorny	A, FW, Or	+	Pods and leaves browsed
Pongomia pinneta (Derris indica)	Lowland and midland humid tropics, salt-tolerant	Small tree to 8 m	FW, A, CT, ST, FI	-	
Prosopis cineraria	Dry zones, heat-resistant	Tree to 8 m, thorny	SF, GM, A, T, DS, FW	0	Higly valued in Indian desert
Prosopis juliflora	Dry zones, tolerant of heat and alkalinity	Tree to 10 m, coppices	FW, GM, A, DS, SC, WLR	+	Widely lopped for fodder in India
Pterocarpus marsupium	Dry to subhumid lowland tropics	Tree to 30 m, coppices well	A, FW, T	+	Widely lopped for fodder in India
Samanea saman	Highland to lowland tropics	Spreading tree to 40 m, fast growing	T, Or, CT, A, F	-	Pods good for human and animal consumption
Sesbania spp. *(bispinosa, grandiflora rostrata, sesban*	Lowland humid to midland semihumid	Low tree, very fast growing; some are annuals *(S. sesban)*	GM, A, SC, SF FW, PW, Or	+	Widely used
Tamarindus indica	Wide adaptability	Large tree to 30 m	F, A, CT, FW, ST	-	Pods rich in vitamin C

Note: 1. A = animal feed (pods, leaves, bark, etc.), BF = bee forage, CT = construction/craft timber, DS = dune stabilization, F = food (human consumption), Fi = fiber, FW = fuelwood, GM = green (leaf) manure, Or = ornamental, PW = pulpwood, T = timber, SC = soil conservation, SF = soil fertility improvement, ST = shade tree (over cacao, coffee, tea), WLR = wasteland reclamation 2. + = reported to nodulate, - = reported not to nodulate, 0 = no report available

Source: Nair (1988)

rates; specific areas of concern are the effect of management and soil conditions on nitrogen-fixation rates, and how much of the fixed nitrogen is made available to current season's crop.

Among the main sources of information on nitrogen-fixing species are the NFTA database (Brewbaker, 1987a) and the ICRAF multipurpose tree and shrub inventory (von Carlowitz, 1987). Lists of the better-known or economically important species are given in MacDicken and Brewbaker (1985) and von Carlowitz (1986). Non-leguminous nodulating species are listed in Bond (1976).

Nutrient Cycling

An advantage commonly attributed to agroforestry and other tree-based systems is that they promote more efficient nutrient cycling than many other systems and thus have a greater potential to improve soil fertility (Nair, 1984). Results from a number of research efforts appear to support this view.

Sanchez (1987), in a review of all available information on this topic, reports encouraging results from experiments conducted to assess the nutrient cycling potential of agroforestry systems on alfisols and andepts of moderate to high fertility. Studies on the use of *Erythrina poeppigiana* as a shade trees in *Coffea arabica* plantations in Costa Rica have also shown good results (Glover and Beer, 1986; Alpizar et al., 1986; Russo and Budowski, 1986; Imbach et al., 1989).

Juo and Lal (1977) compared the effects of a *Leucaena leucocephala* fallow versus a bush fallow on selected chemical properties in alfisols in western Nigeria. After three years, during which the *L. leucocephala* was cut annually and left as mulch, the cation exchange capacity and levels of exchangeable calcium and potassium were significantly higher in the *L. leucocephala* fallow than in the bush fallow. Studies carried out by Agamuthu and Broughton (1985) showed that nutrient cycling in oil-palm plantations where there were leguminous cover crops (*Centrosema pubescens* and *Pueraria phaseoloides*) was more efficient than in plantations where there was no cover crop. In addition to fixing about 150 kg N/ha/yr, the loss of nitrate nitrogen through leaching was significantly lower in the former system.

Young (1989), drawing on studies on the nitrogen content of litter fall and prunings, provides data on various trees species in agroforestry systems in humid and moist subhumid climates, and compares these with data from natural vegetation communities (*see* Table 7). In hedgerow intercropping systems, some species are capable of supplying 100-200 kg N/ha/yr if all the prunings are left on the soil; this is the same as the amount of nitrogen that is removed during harvest in cereal/legume intercropping systems. In coffee and cacao plantations with shade trees (partly nitrogen fixing), the return in litter and prunings is 100-300 kg N/ha/yr, which is much higher than the amount removed during harvest or derived from nitrogen fixation.

A number of studies on soil changes under shifting cultivation have been carried out (Jordan et al., 1983; Toky and Ramakrishnan, 1983; Andriesse and Koopmans, 1984; Andriesse and Schelhaas, 1985). However, there are no data as yet on nutrient cycling in agroforestry systems based on shifting cultivation. The major inefficiency in shifting cultivation is that most of the nitrogen built up in the fallow period is in the vegetation, and much of this nitrogen is lost when the vegetation is burned.

Some tree and shrub species can selectively accumulate certain nutrients, even in soils which contain very small amounts of these nutrients. Palms, for example, are able to accumulate large amounts of potassium (Foelster et al., 1976), tree ferns accumulate nitrogen (Mueller-Dombois et al., 1984), *Gmelina* accumulates calcium (Sanchez et al., 1985) and *Cecropia* species growing on acid soils appear to accumulate calcium and phosphorous (Odum and Pigeon, 1970). However, as Golley (1986)

Table 7. Nitrogen content in litter fall and prunings

Country and climate	Land use	Nitrogen (kg/ha/yr)	Source
Nigeria, subhumid	Hedgerow intercropping, 4 m rows, prunings:		Kang and Bahiru Duguma (1985)
	Leucaena leucocephala	200	
	Gliricidia sepium	100	
Nigeria, subhumid	Hedgerow intercropping, 2 m rows, prunings:		Bahiru Duguma et al. (1988)
	Leucaena leucocephala	150-280	
	Gliricidia sepium (6 months)	160-200	
	Sesbania grandiflora (6 months)	50-100	
Venezuela, subhumid	Coffee-*Erythrina-Inga* (unfertilized):		Aranguren et al. (1982)
	trees only	86	
	trees and coffee	172	
	Cacao-*Erythrina-Inga*		Aranguren et al. (1982)
	trees only	175	
	trees and cacao	321	
Costa Rica, humid	Cacao-*Cordia alliodora* (fertilized)	115	Alpizar et al. (1986, 1988)
	Cacao-*Erythrina poeppigiana* (fertilized)	175	
Various humid	Rain forest	60-220	Bartholomew (1977)
Various, humid	*Leucaena leucocephala*, plantation:		BOSTID (1984)
	foliage	500-600	
	litter fall	100	
18 sites, humid	Forest	mean 134	Lundgren (1978)
Côte d'Ivoire, humid	Rain forest	113, 170	Bernhard-Reversat (1977)
Brazil, humid	Rain forest	61	Jordan et al. (1982)
California USA, arid	*Prosopis glandulosa* (woodland)	45	Rundel et al. (1982)

Source: Young (1989)

points out, the ability to accumulate nutrients varies according to particular sites and soils, and this factor must be taken into account when selecting nutrient-conserving species for incorporation into agroforestry technologies.

It is likely that the nutrient status of soils beneath trees is improved through canopy capture of precipitation inputs (Kellman, 1979), but this needs further investigation.

The nitrogen cycle

It is important at this point to distinguish between nitrogen fixation, an input into the plant-soil system, and nitrogen addition (through litter or prunings), which involves internal process in the soil.

Much of the nitrogen in litter is taken up from the soil, originating either from stored reserves in the soil or from fertilizers. Therefore, two important questions arise:

- How much nitrogen is fixed by the tree component in agroforestry systems?
- How does this component improve the efficiency with which the nitrogen contained in the soil is supplied to the crop?

To answer these questions, studies on nitrogen balance must be carried out, taking into account the inputs and outputs of the plant-soil system as well as the internal processes. Data on atmospheric input, non-symbiotic fixation, gaseous losses and leaching are seldom obtained in non-specialized trials, and must be estimated by comparison with specialized studies conducted in similar environmental conditions.

Trees and Biomass Production

Young (1989) argues that the rates of net primary production (above-ground dry matter) under natural ecosystems serve, in two ways, as a useful reference point for assessing the value of biomass production from trees in agroforestry systems. First, they indicate the relative biological productivity that can be expected under different climates. Second, they provide the minimum rates to be expected, assuming that in agroforestry systems the combined effect of species selection and management will result in higher rates of biomass production than in monocultural systems.

On average, the rate of biomass production of evergreen rainforest is estimated to be 20,000 kg/ha/yr (although for some sites it may be half this amount, and for others it may reach 40,000 kg/ha/yr). In semi-deciduous forest, the typical rate is also about 20,000 kg/ha/yr, while in high-altitude forest the rate is slightly lower (Lundgren, 1978). In savanna communities, the typical rate varies from 10,000 kg/ha/yr for moist savanna to 5,000 kg/ha/yr for dry savanna. In desert scrub areas the rate is 2500 kg/ha/yr or less.

From his studies of natural ecosystems, Young (1989) suggests that the net primary production rates which can be expected in various climatic zones are:

Humid tropics with no dry season	20,000 kg/ha/yr or more
Humid tropics with a short dry season	20,000 kg/ha/yr
Moist subhumid tropics	10,000 kg/ha/yr
Dry subhumid tropics	5,000 kg/ha/yr
Semi-arid zone	2,500 kg/ha/yr

The leaf biomass production rates of various multipurpose trees, grown in agroforestry systems or as plantations, are given in Table 8. These results are fragmentary, but more data from trials currently under way will soon be available. The hedgerow intercropping data in the table refer to the tree component of these systems. In the IITA project from which the Nigerian data are drawn, the tree rows are 4 m apart, and thus occupy about 25% of the total ground area; the project site lies on the margin between the moist subhumid and humid zones. If the crop net primary production of about 10,000 kg/ha/yr (from two crops) is added, the total biomass production is about 15,000 kg/ha/yr. This is the rate that might be expected in natural ecosystems in this climatic zone. Thus, the typical rate of leaf biomass production of multipurpose trees in hedgerow intercropping in this zone is between 2,000 and 4,000 kg dry matter or 8 to 16 t fresh matter. The rates for leaf fodder production given in the ICRAF multipurpose tree and shrub database are even lower, mostly a few hundred kilograms per hectare per year (von Carlowitz, 1986); this may be because there are fewer fodder trees per unit area

Table 8. Leaf biomass production of multipurpose trees (kg DM/ha/yr)

Country	Land use	Tree	NPP	Source
		HUMID		
Malaysia	Plantation	*Acacia mangium*	3060	Lim (1985)
Philippines	Plantation	*Albizia falcataria*	180	Kawahara et al. (1981)
Costa Rica	Hedgerow intercropping	*Calliandra calothyrsus*	2760	Baggio and Heuveldorp (1984)
Philippines	Plantation	*Gmelina arborea*	140	Kawahara et al. (1981)
Java	Plantation	*Leucaena leucocephala* *Albizia falcataria* *Dalbergia latifolia* *Acacia auriculiformis*	3000- 5000	Buck (1986)
Costa Rica	Plantation crop combination	*Cordia alliodora*	2690	Alpizar et al. (1986, 1988)
		Cordia alliodora and cacao	6460	
		Erythrina poeppigiana	4270	
		Erythrina poeppigiana and cacao	8180	
		MOIST SUBHUMID BIMODAL		
Nigeria	Hedgerow intercropping	*Cajanus cajan*	4100	Agboola (1982)
Nigeria	Hedgerow intercropping	*Gliridicia sepium*	2300	Agboola (1982)
Nigeria	Hedgerow intercropping	*Leucaena leucocephala*	2470	Agboola (1982)
Nigeria	Hedgerow intercropping	*Tephrosia candida*	3070	Agboola (1982)
		SUBHUMID		
India	Plantation	*Leucaena leucocephala*	2300	Mishra et al. (1986)

Source: Young (1989)

and lower levels of management than in the IITA project. In summary, the biomass production from the tree component in agroforestry systems can approach that in natural ecosystems in the same climatic zone, and may exceed it if improved species are used.

In evaluating the contribution of tree biomass production towards maintaining soil organic content, it is essential to establish which of the four plant components of this biomass — leaf (herbaceous), reproductive (fruit and flower), wood and root — will be harvested and which will be returned to the soil. This depends on several factors, including the particular tree species, the environmental conditions and the management levels and practices. For example, root growth is less affected by nutrient stress than above-ground shoot growth, the removal of fruit increases vegetative growth and the repeated removal of vegetative parts through such practices as pruning adversely affects future vegetative growth.

For the three climatic zones of the tropics, Young (1989) has provided general estimates of the amounts of above-ground dry matter that need to be added to the soil to maintain soil organic content (*see* Table 9). In the humid tropics the required amount is 8,000 kg/yr; in the subhumid and semi-arid zones the required amounts are 4,000 and 2000 kg/yr, respectively. It is possible to meet these requirements if the total tree biomass is added to the soil, and even more so if herbaceous crop residues are also added. However, if the woody component of the tree is harvested, it would be more

Table 9. Plant biomass amounts required to maintain soil organic content in different climatic zones of the tropics

Climatic zone	Initial topsoil carbon (kgC/ha)	Topsoil carbon (%)	Oxidation loss (kgC/ha/yr)	Erosion loss (kgC/ha/yr)	Required addition to soil humus (kgC/ha/yr)	Required plant residues added to soil (kgC/ha/yr)	
						above ground	roots
Humid	30,000	2.0	1,200	400	1,600	8,400	5,800
Subhumid	15,000	1.0	600	200	800	4,200	2,900
Semi-arid	7,500	0.5	300	100	400	2,100	1,400

Source: Young (1989)

difficult meet these requirements, and if tree foliage and crop residues are also removed, it would be impossible.

Trees and Soil Conservation

The rates of soil erosion under agroforestry and other tree-based systems have been reviewed by Wiersum (1986) and, more recently, by Young (1989). The following summary is based on Young's review.

Effect of trees on factors of erosion

- *Rainfall erosivity:* Raindrops falling on high tree canopies coalesce into larger drops, which then fall with a greater velocity than smaller raindrops. Higher rates of erosion caused by this factor have been recorded in forest plantations than in natural forests. Erosion rates recorded in a homegarden (Soemarwoto, 1987) and a multistorey tree garden were higher than those recorded in forest. It may be assumed that a low and dense canopy would reduce erosivity, but as yet there are no measurements to substantiate this. Under alley cropping, although the canopy is low, it is not directly above the cropped land.

- *Soil erodibility:* Soil structure is of a higher grade and more stable, with lower detachability and higher infiltration capacity, under forest than under cultivation. Under shifting cultivation, organic matter declines and erodibility increases during the cropping period. Under taungya systems, there is usually a decline in organic matter and infiltration capacity and an increase in erosion during the cropping period. Alley cropping has the potential to maintain organic matter, or reduce the rate at which it decreases, whereas under monocropping there is almost invariably a decline in organic matter.

- *Run-off:* It is well known that grass strips, bunds, terraces and other soil-conservation structures reduce run-off and erosion, but it seems that no specific advantage is gained by the presence of trees on these structures. Barrier hedges seem to be effective in reducing run-off, as do the natural terraces formed by tree rows in alley cropping (Bannister and Nair, 1990), but in both cases there are insuffícent data to substantiate this.

- *Ground surface cover:* The surface litter cover is far more important than the leaf canopy in controlling erosion. In plantation crop combinations, leaving prunings on the ground reduces erosion substantially. In a multistorey tree garden in Tanzania, when crop residues were left as mulch, less erosion occurred than in forest. There are two reports of higher erosion occurring under trees on pastures than in pure pastures, but neither report suggests possible reasons for this.

Observed erosion rates

Recorded erosion rates under agroforestry and other tree-based systems are shown in Table 10. Taking low rates of erosion as less than 2 t/ha/yr, moderate rates as 2-10 t/ha/yr, and high rates as over 10 t/ha/yr, these systems can grouped as follows:

Low	Natural rain forest; forest fallow in shifting cultivation; multistorey tree gardens; most forest plantations (undisturbed); tree plantation crops with cover crop and/or mulch
Moderate or high	Cropping period in shifting cultivation; forest plantations, litter removed or burned; taungya, cultivated; tree crops, clean weeded

The data show that in the systems which have high erosion potential, the range of values is large. This indicates that management practices, rather than particular types of land use, are more important in minimizing erosion potential.

Table 10. Rates of soil erosion in tropical ecosystems

	Erosion (t/ha/yr)		
Land-use system	**Minimum**	**Median**	**Maximum**
Multistorey tree gardens	0.01	0.06	0.14
Natural rain forest	0.03	0.30	6.16
Shifting cultivation, fallow period	0.05	0.15	7.40
Forest plantation, undisturbed	0.02	0.58	6.20
Tree crops with cover crop or mulch	0.10	0.75	5.60
Shifting cultivation, cropping period	0.40	2.78	70.05
Taungya, cultivation period	0.63	5.23	17.37
Tree crops, clean weeded	1.20	47.60	182.90
Forest plantations, litter removed or burned	5.92	53.40	104.80

Source: Wiersum (1986)

It is clear that maintaining a surface cover of plant litter, which is possible in most agroforestry sytems, is the most effective way of reducing erosion. There are several types of agroforestry practices which, with good management, have the potential to reduce erosion to acceptable levels; these include multistorey tree gardens, planted tree fallows, alley cropping, plantation crop combinations, multi-purpose woodlots and reclamation forestry. In all these cases, however, what matters is not simply the presence of trees but the way in which the system is designed and managed. In designing a system for erosion control, the major aims should be to ensure a good surface cover of plant litter and to provide effective barriers against erosion by appropriate row alignment. Maintenance of soil organic matter, and hence of the soil's physical properties and ability to resist erosion, is also important. Erosion control based on tree-canopy protection is unlikely to be effective, except possibly where the canopy is low and dense.

Windbreaks and shelterbelts

Where wind is a major cause of soil erosion and moisture loss, a properly designed and maintained windbreak reduces the speed of the wind and thus its ability to carry and deposit soil and sand. Windbreaks can also improve the microclimate of an area by reducing water evaporation from the soil and plants, and in some cases they may increase plant producivity. An added advantage is that they can provide a wide range of useful products, such as poles, fuelwood, fruit, fodder, fiber and mulch.

Windbreaks usually consist of narrow, multistorey strips of trees and shrubs planted at least three rows deep. They are placed on the upwind side of the land to be protected, at right angles to the prevailing wind. They vary considerably in length and height. On the dry savannas and steppes of Africa they are usually 100 m or more in length, with a maximum height of 10 m. Shelterbelts are a form of windbreak, but are planted many rows deep.

To be effective, a windbreak must be specifically designed to slow the wind. Very dense windbreaks may do more harm than good, as they will tend to create strong turbulence that will scour the soil on the windward side and damage crops on the leeward side. Gaps in the trees will channel the wind; this will increase wind velocity on the leeward side, resulting in soil erosion and crop damage. Field examples of the use of windbreaks for environmental protection are given in Chapter 3. Low-growing hedgerows and live-fences can protect small units such as homegardens and nurseries from the wind, but are not specifically designed to act as windbreaks.

PRODUCTIVITY OF MIXED PLANT COMMUNITIES

How a plant influences its neighbors, and to what extent this influence is beneficial or detrimental, is a central issue in analyzing plant interactions in mixed crop communities. Harper (1977) effectively summarized the issue thus: 'A plant may influence its neighbors by changing their environment. The changes may be by addition or subtraction and there is much controversy about which is more important. There may also be indirect effects, not acting through resources or toxins, but affecting conditions such as temperature or wind velocity, encouraging or discouraging animals and so affecting predation, trampling, etc.'

The interaction between neighboring plants is often described as 'competitive'. This is because interference between plants lowers their rate of absorption of growth factors, relative to plants grown in isolation, and thus promotes competition between plants for growth factors. If the components of a plant community are the same species (as in sole cropping), or are similar morphologically, and have a limited pool of resources to draw on, then the plants most likely to thrive — the successful competitors — are those that are able to exploit these resources most efficiently. However, interaction between neighboring plants should not be seen only in terms of competition *for* resources, but also in relation to such processes as the transfer of microbially fixed nitrogen, the action of biologically active plant exudates (allelopathy) and interactions concerning parasitic micro-organisms and nematodes, herbivorous insect pests and other types of organisms.

Managing a mixed plant community effectively depends upon understanding the processes involved and using designs and mixtures that will minimize competition, prevent unfavorable biological interferences and exploit beneficial interactions. There is now a large amount of research data on the ecology of intercropping annuals, as the review by Vandermeer (1989) shows, but few detailed studies have been conducted on plant interactions in communities consisting partly of woody perennials.

The work that has been done indicates that in perennial-annual mixtures, the perennial usually has a greater and more long-lasting effect on the environment, and this adversely affects the performance of the annual. According to the competitive production principle, a mixture becomes successful only when both components can exploit available resources more efficiently when grown together than when grown in monocultural situations. The facilitative production principle may also come into play; that is, the environment of one species (usually the annual) is modified by the presence of a second species (the perennial) in such a way as to facilitate the growth of the first species. Often, these principles operate simultaneously and inseparably. The net effect of these interactions will manifest itself in terms of the performance of the individual plants and of the system as a whole.

Above-Ground Interactions

It is common knowledge that the rate of photosynthesis depends upon the intensity of light, the rate being rapid at lower intensities and slow at higher intensities. However, plants vary considerably in their response to light intensities in terms of growth rates and competitive ability. A plant's physical architecture is one of several characteristics that decides its pattern of response to light intensities.

Understanding the way in which the components of a mixed plant community share light and solar radiation is a key factor in managing above-ground plant interactions in agroforestry. Some of the available light and solar radiation is intercepted by the top layers of leaves of the overstorey species, while the rest of it is available to the understorey species. The curve of net photosynthesis saturates at 20% of full sunlight, and therefore any leaf receiving more than this intensity should (theoretically) operate at full capacity. We could thus have a multistorey plant configuration where, for every unit of ground area, there is half a unit of leaf area at or near the top receiving full sunlight, half a unit of leaf area some distance down receiving 50% full sunlight, but able to photosynthesize at full capacity, and yet another layer of leaves further down with leaf area equal to ground area, receiving only 25% of full sunlight but still able to photosynthesize at full rate. Thus, there could be twice as much leaf area as ground area, with all leaves operating at the peak photosynthetic rate.

There is considerable scientific data showing that, under practical field conditions, mixed plant communities have a better photosynthetic efficiency than monocultural stands. Although the leaf area index in a monocultural stand often exceeds 2, the leaves in the stands do not all photosynthesize at full capacity.

Below-Ground Interactions

In mixed plant communities, the key factor in below-ground interactions is the structure and efficiency of the root systems of individual components, which determine the uptake of and competition for nutrients and moisture. Roots are a component of primary productivity, although they are seldom considered in conventional plant productivity calculations. Whereas the roots of annuals function on a seasonal basis, tree roots need to function all year round. They also change their own environment by accumulating litter and redistributing nutrients. Trees have to contend with many changes in growth conditions, and thus they require efficient root systems which have the ability to form a stable base, as well as the flexibility to accommodate changes quickly (Bowen, 1985). In competitive environments, survival is the goal, and this will have a bearing on how much root it is 'necessary' for a tree to have.

Root biomass, turnover and nutrient storage

The root biomass of trees is usually 20-30% of total plant biomass, although it may be as low as 15% in some rain forests or as high as 50% or more in semi-arid and arid vegetation. This biomass consists of structural roots (medium to large diameter and relatively permanent), fine roots (less than 2 mm diameter) and mycorrhizae. Root abundance is expressed in terms of area (cm/cm^2 of soil surface) or density (cm/cm^3 of soil volume). In general, rooting densities of trees are lower than those of cereals and herbaceous legumes (Bowen, 1985). The rooting density and distribution of a particular plant depends on various site-related factors. Combining trees and crops increases rooting densities and reduces inter-root distances, which increases the likelihood of inter-plant competition (Young, 1989).

One of the main difficulties in assessing the root biomass of trees by conventional core sampling or excavation methods is that the annual net primary production of roots is substantially more than the standing biomass found at any one time. This is mainly because fine roots are continuously being sloughed off, and new ones regenerated (Sauerbeck and Johnen, 1977; Sauerbeck et al., 1982), and thus the proportion of total photosynthate which passes into the root system is much higher than the standing biomass would suggest (Coleman, 1976; Herman, 1977; Fogel, 1985). In some respects, then, the build up and regeneration of the root system is similar to that of the above-ground biomass: the structural roots are comparable with the trunk and branches in having a steady increment and slow turnover, whereas the feeder roots, like the leaves, fruit and flowers, are subject to shedding and regrowth (Young, 1989). Likewise, above-ground litter fall and below-ground root turnover both serve to improve soil organic matter; this function of root turnover continues even when above-ground biomass is removed. Root turnover, and the effect of this process on soil organic matter, is a critical factor in the evaluation of agroforestry systems. The fine-root biomass data reported by Jonsson et al. (1988) from Morogoro, Tanzania (subhumid climate) for two-year-old *Eucalyptus tereticornis* (532 kg/ha), *Leucaena leucocephala* (616 and 744 kg/ha) and other species are one-off figures and thus unlikely to represent the total root biomass production of the plants.

Roots also store considerable quantities of nutrients. Jordan et al. (1983) reported that in a rain forest on a ferralsol, 10% of plant nitrogen occurred in the root system; in a forest on a nutrient-poor podzol, the figure was 40%. Koopmans and Andriesse (1982) and Andriesse et al. (1987) reported the following percentages and amounts of nutirents stored in root systems at two sites in successional forest fallows of shifting cultivation in Sri Lanka and Malaysia: nitrogen 0.67%, 76 kg/ha; phosphorus 0.04%, 3.5 kg/ha; and potassium 0.57%, 53 kg/ha. Mycorrhizal associations (symbiotic associations between roots and soil fungi) are also important. Mycorrhizae absorb carbohydrates from the host plant, which has the effect of expanding the root system and thus increasing nutrient absorption. When trees are introduced into a system, mycorrhizal inoculation, like *Rhizobium* inoculation, will be extremely beneficial.

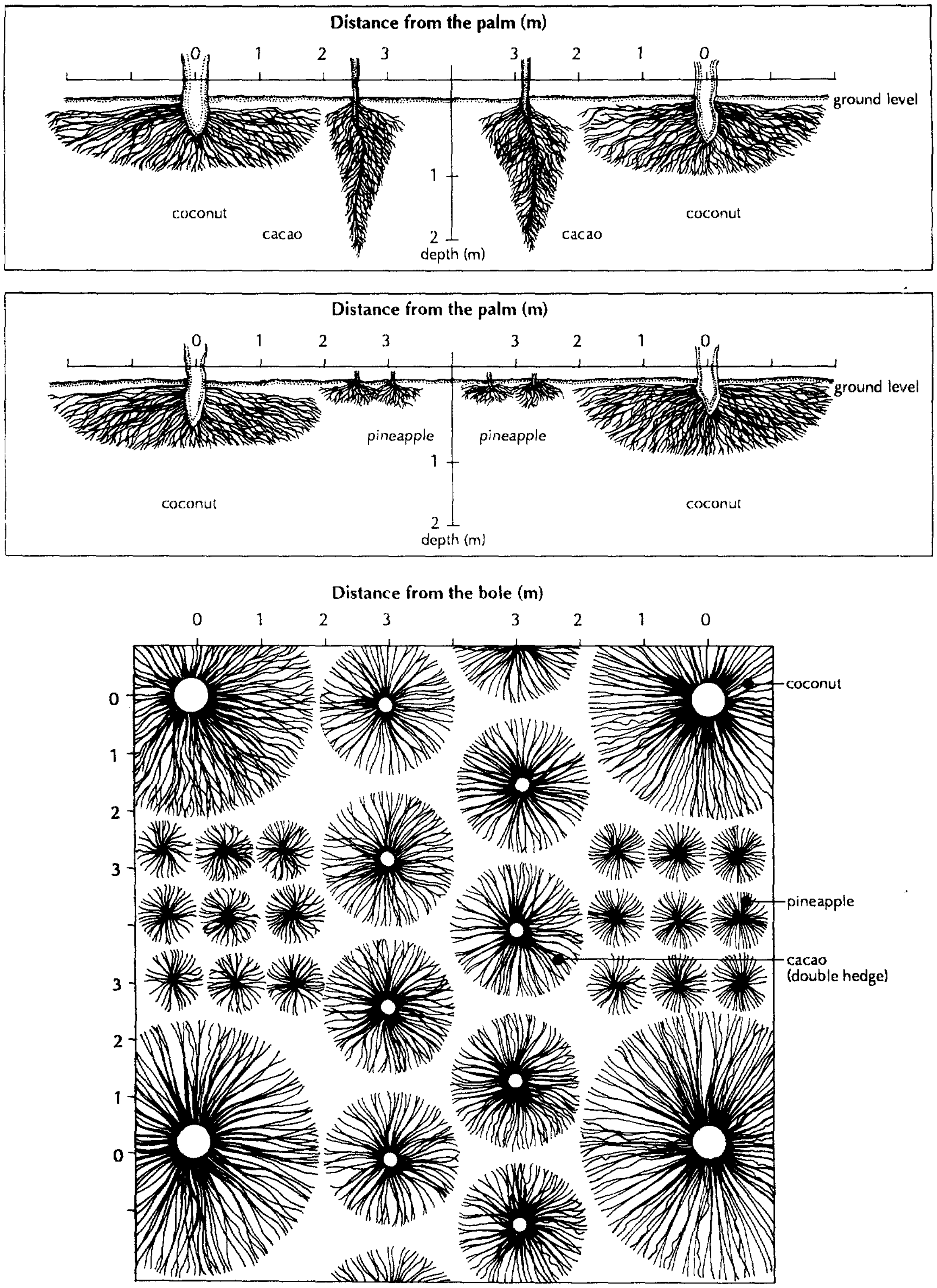
Effect of root interactions on soil fertility

One of the most important aspects of below-ground interactions in agroforestry is competition for the growth factors which are absorbed through roots — nutrients and water. Complementary interactions have been reported, but are far less significant than competitive interactions. To avoid or minimize the effects of this competition, the rooting patterns of trees and crops should differ in terms of structure and depth. Nair (1979) has postulated that the concept of multistorey plant combinations should incorporate both above-ground and below-ground configurations. Figure 2 is a schematic representation of the rooting pattern of a multistoried combination of coconut, cacao and pineapple.

The deep-rooting characteristics of trees are often cited as being desirable for agroforestry systems. This is based on the assumption that, because of their deep roots, trees are able to absorb nutrients from soil depths that crop roots cannot reach (Nair, 1984). However, data are needed to substantiate this. Most of the fine, feeder roots of many common trees are found within the 20 cm-deep topsoil (Commerford et al., 1984). Radio-tracer techniques have been used extensively in studies of the root systems of horticultural tree crops, such as cacao (Ahenkora, 1975), apple (Atkinson, 1974), coffee (Huxley et al., 1974) and guava (Purohit and Mukherjee, 1974), but most of these studies have focused on the extent of the root systems, rather than on variations in uptake according to different soil depths. These studies have also shown that although subsoil nutrients can play an important role in orchard tree nutrition, nutrient uptake is not directly proportional to root weight.

The contribution of roots to soil organic matter, and thus to soil fertility, has received little serious attention. The ability of the root system to improve soil organic matter even where all above-ground biomass is removed, as discussed earlier, is a crucial factor in low-input agricultural systems, albeit

Figure 2. Schematic presentation of the vertical (above) and horizontal (below) distributions of root systems of different crops in a multistorey crop combination of coconut, cacao and pineapple



Source: Nair (1979)

under low productivity levels. This emerges clearly from the data presented by Ewel et al. (1982), comparing root biomass with leaf biomass (not total above-ground biomass) for a range of land-use systems in Costa Rica (*see* Table 11). These data also show that total root biomass in agroforestry systems is substantially higher than in other land-use systems.

Table 11. Leaf and root biomass in nine land-use systems (kg/ha)

	Agricultural systems			Forest systems		Agroforestry systems			
	Young maize	Mature maize	Sweet potato	*Gmelina* plantation	Secondary forest	Coffee-*Erythrina*	Cacao-*Cordia*	Tree garden	Planted fallow
Leaf biomass	330	1,000	1,070	3,120	3,070	2,720	2,040	2,450	2,480
Root biomass (to 25 cm)	390	1,150	410	1,280	2,170	2,350	2,720	3,070	4,220
Roots:leaves ratio	1:18	1:15	0:38	0:41	0:71	0:86	1:33	1:25	1:70

Source: Ewel et al. (1982)

The key to making the best use of below-ground interactions in agroforestry lies in maximizing their positive effects and reducing tree-crop competition. Undoubtedly, we need to know more about these interactions. When research reaches the point of designing plant ideotypes for agroforestry systems, the rooting characteristics of component species will be an important criterion.

Effect of Species Diversity on the Ecology

Ewel (1986) argues that there are three potential ecological benefits of having several species in an ecosystem: full use of resources, pest protection and compensatory growth.

An increase in species diversity and richness does not always lead to a more effective use of resources but, in many mixed plant communities, resource use is complementary rather than competitive (Connor, 1983; Willey, 1985). As indicated above, there are various mechanisms by which these communities use and share above- and below-ground resources, but in most agrosystems this pool of resources is limited. Therefore, the benefits of pest protection and compensatory growth are sometimes just as relevant to agroforestry systems as full use of resources.

Several factors have been cited to support the contention that mixed plant communities offer increased pest protection (for example, dense vegetation, comprising various plant forms, inhibits the movement of pests). However, plant diversity can also lead to an increase in pest damage if one plant species in a community acts as an alternate host to the pest of another plant species.

Compensatory growth refers to the process by which one species takes over and maintains the full use of resources if another species succumbs to disease, pest attack, unfavorable weather conditions and so on. Agriculturally, this is an important factor because it reduces the risk of total crop failure by spreading the risk among several components (Ewel, 1986).

There are also particular benefits of a mixed species system which includes woody perennials. For example, the continuity of cover provided by these perennials may reduce soil erosion, lower the rate of evaporation from the soil, ameliorate the microclimate and allow nutrients to circulate without interruption. Their extensive root systems can also lead to fuller and more efficient use of soil resources than is the case in monocultural systems; however, it is not known whether the root systems of tree monocultures can exploit these resources as efficiently as stands of mixed tree species. The disadvantages of tree-based mixed species systems include the fact that the yield of annual crops is usually much higher than that of perennials. Annuals have high net primary productivity, much of which is allocated to the reproductive or storage organs that are harvested for food or other purposes, whereas only a small proportion of the total biomass of perennial crops is harvested, except perhaps in the case of species grown specifically to provide fuelwood.

The advantage offered by agroforestry is that it is possible to combine the ecological benefits of perennial polycultures with the high yields that can be obtained from the monoculture of annuals.

Measuring the Productivity of Mixed Plant Communities

The method most frequently used to measure the effectiveness of intercropping is the Land Equivalent Ratio (LER). Originally proposed as a means of comparing the performance of a species in an intercropping situation with its perfomance when grown as a sole crop (IRRI, 1974; 1975), it is so called because it refers to the relative land requirements of intercropping versus monocropping (Mead and Willey, 1980).

LER is the sum of the relative yields of the component species, represented thus:

$$\text{LER} = \sum_{i=1}^{m} \frac{Yi}{Yii}$$

where

Yi is the yield of the 'i'th component from a unit area of the intercrop;
Yii is the yield of the same component grown as a sole crop over the same area;
and $\frac{Yi}{Yii}$ is the relative yield of component i.

To illustrate how LER is calculated, let us assume that on 1 ha of land it is possible to produce 10 units of a tree product and 50 units of a crop product when they are grown together. However, when they are grown as sole crops, 0.75 ha is needed to produce the same 10 units of the tree product and 0.5 ha to produce the same 50 units of the crop product. Thus, whereas in the former case the total area of land needed to produce the given amount of products is 1 ha, in the latter case the area needed is 1.25 ha; that is, the LER is 1.25. This figure indicates that there is an advantage in growing the species together. Had the LER been 1, this would indicate that neither system had an advantage over the other, but if it had been less than 1, the sole cropping system would have had the advantage.

If an LER measurement is made on the basis of uniform overall density of the crop, then it will be equal to the relative yield total (RYT). However, in most agroforestry systems, the plant density of a component species may differ from that of the same species when monocropped, and LER values may vary with general density levels of the species. Although the definition of LER requires that the sole crop used in calculations be at its optimum density, few LER measurements have been made using sole crop data from a range of densities. If the performance of an intercrop is to be compared with that of a sole crop at its optimum density, it would be necessary to use the intercrop's performance measured at its own optimum density. This would be a tedious operation, and thus constant density LER (RYT) is normally used when the aim is to identify beneficial crop combinations (Nair, 1979).

One criticism of LER is that, when used for associations of crops with different durations, it may overestimate land-use efficiency. The method proposed by Hiebsch and McCollum (1987), known as Area Time Equivalency Ratio (ATER), takes both the time factor and the land area into account, but it is likely to underestimate the advantages of intercropping (Balasubramanian and Sekeyange, 1990). As a compromise, some researchers use the mean value of LER + ATER. An alternative approach is to use Area Harvest Equivalency Ratio (AHER), which combines the area and time factors for quantifying intercrop advantages (Balasubramanian and Sekeyange, 1990). However, none of these methods, when applied to an agroforestry system, reflects the sustainability of the system, which is one of the main attributes of agroforestry. One way to overcome this difficulty would be to include multiple products and their values in a calculation based on any of these approaches, observe the changes in values from year to year over a long period of time, and relate these values to a sustainability index. Another useful measure is the Income Equivalent Ratio (IER), which is similar to LER but focuses on the income, rather than the production, from individual components.

In time-dominated or interpolated agroforestry combinations, LER-type measurements may not be relevant at all. For example, when annual crops are intercropped with perennial plantation crops during the latter's early stages of growth, the farmer is not concerned with joint maximization of the two commodities (maximizing LER) but, rather, with maximizing production from the annual crop without significantly reducing the growth rate of the plantation species.

In spite of their limitations, LER-type measurements are useful in assessing the merits of particular plant combinations. However, as the above discussion shows, they need to be modified if they are to be used effectively in agroforestry research and evaluation.

Chapter 3

Improved Practices and New Approaches

The scientific principles discussed in the previous section strengthen the conceptual framework of agroforestry. However, most of them are based on indirect evidence, and some have only a peripheral relevance to agroforestry. Their validity has yet to be fully tested in the field. Whether such tests should be carried out on farm or on station, or both, is debatable; an appropriate combination of both is probably the best option, although it is difficult to achieve. What is clear, however, is that the current state of knowledge of agroforestry, coupled with institutional and resource constraints, is such that none of these options would, as yet, produce definitive conclusions.

Nevertheless, some commendable agroforestry research projects are under way in various places in the tropics. The vast majority of them focus on alley cropping (and other hedgerow intercropping practices) or plantation crop combinations. In the first part of this chapter we evaluate these two practices, and conclude with a brief look at some other agroforestry practices. In the second part, we discuss new approaches of particular significance for Africa, where the need to find solutions to overwhelming land-use problems is now critical.

EVALUATION OF RECENT RESEARCH ON AGROFORESTRY PRACTICES

Alley Cropping

Nutrient yield

With the growing emphasis on the role of nitrogen-fixing trees in soil-fertility improvement in agroforestry systems in general and alley cropping in particular (Brewbaker et al., 1982; Dommergues, 1987; Nair, 1988), there is increasing interest in obtaining more field data. As the data in the previous chapter show, there are great variations in the estimates of nitrogen fixation by different tree species, and it is clear from this and other research results that much more information is needed.

The nitrogen yield of woody perennials (that is, the amount of nitrogen made available from the decomposition of biomass added to soil) is perhaps the most important source of nitrogen for agricultural crops in alley cropping. It varies according to the biomass yield of the trees, which in turn depends on the species and on management and site-specific factors.

Some data on the biomass yield of four woody species growing on alfisols in Ibadan, Nigeria under different management systems are provided in Table 12. Data from alley cropping studies conducted in Costa Rica by the Centro Agronomico Tropical de Investigacion y Enseñanza (CATIE), in which *Erythrina poeppigiana* was grown as a hedgerow species, are also available (Kass, 1987). Torres (1983) estimated that the annual nitrogen yield of *Leucaena leucocephala* hedgerows, cut approximately every eight weeks, was 45 g per meter; if the hedges were planted 5 m apart, this amounted to 90 kg N/ha/yr. Higher yields have been reported from field studies of hedges which consisted of nitrogen-fixing species, especially *Leucaena* and *Gliricidia* (Yamoah et al., 1986b; Budelman, 1988). In a comparative study of the effect of various pruning practices on *Leucaena*, *Gliricidia* and *Sesbania*, Duguma et al. (1988) found that, for all three species, the highest yields were obtained from bi-weekly prunings to 100 cm (245.1, 205.6 and 110.8 kg N/ha/yr, respectively). However, it should be noted that this pruning practice is very labor intensive and, in drier areas, is biologically unfeasible.

Table 12. Average pruning yields from woody species alley-cropped with food crops at IITA, Nigeria

Species [1]	Pruning yield (t DM/ha/yr)
Acioa barterii	2.07
Alchornea cordifolia	3.77
Gliricidia sepium	5.18
Leucaena leucocephala	8.64
LSD (0.05)	1.52

Note: Three-year old hedgerows; 25 cm between plants in a row; rows spaced 2 m and 4 m apart; hedgerows pruned five times a year; fertilizers applied to accompanying crops at two different levels: 45-20-20 and 90-40-40 N, P and K kg/ha, respectively

Source: Kang et al. (1989)

Hedgerow prunings are also an important source of other nutrients. Table 13 gives the nutrient yield data from studies carried out at IITA, Nigeria. In studies conducted in Côte d'Ivoire, yields of 44, 59 and 37 kg of K/ha were obtained over a period of three months from *Gliricidia sepium*, *Leucaena leucocephala* and *Flemingia macrophylla*, respectively (Budelman, 1988).

Table 13. Nutrient yield from five prunings of hedgerows of five woody species grown at IITA, Nigeria (4 x 0.5 m spacing)

Species	Nutrient yield (kg/ha/yr)				
	N	P	K	Ca	Mg
Acioa barterii	41	4	20	14	5
Alchornea cordifolia	85	6	48	42	8
Gliricidia sepium	169	11	149	66	17
Leucaena leucocephala	247	19	185	98	16

Source: Kang et al. (1989)

Although the amount of data on these aspects of alley cropping is growing, more research needs to be done on the extent to which the nutrients produced by the hedgerow species will meet the nutrient requirements of the crop(s) grown in the alleys at critical stages of crop growth. Some information is available on the decomposition pattern and nutrient release characteristics of some hedgerow species. Budelman (1988) reported that the decomposition half-lives of *Leucaena leucocephala*, *Gliricidia sepium* and *Flemingia macrophylla* were 30.7, 21.9 and 53.4 days, respectively; these half-lives were correlated with *in vitro* digestibility of organic matter, although the digestibility of *Flemingia* was half that of the other two species. During a 120-day field study of the decomposition rates of hedgerow leaves, prunings from *G. sepium*, *F. congesta* (*macrophylla*) and *Cassia siamea* exhibited dry-matter losses of 96%, 58% and 46%, respectively. Nitrogen mineralization from *G. sepium* supplied 71% of the nitrogen needed for maize production, while *Flemingia* supplied only 26% (Yamoah et al., 1986a).

From a similar study in the Peruvian Amazon basin, Palm and Sanchez (1988) reported that leaves of *Gliricidia sepium* had significantly higher levels of nitrogen mineralization than did the leaves of 10 other local tree species. From the same site, Palm (1988) found that the ratio of soluble phenolics to nitrogen was a better indicator of likely nitrogen release. These studies show that, on the high acid soils of the Peruvian Amazon basin, *G. sepium* and *Erythrina* species are suitable for nutrient enrichment use, while *Inga edulis* and *Cassia siamea*, because of the slow rate of decomposition of their leaves, could be used for erosion control and to provide soil organic matter.

Effect on soil properties and soil conservation

One of the most important premises of alley cropping is that the addition of organic mulch, especially nutrient-rich mulch, has a favorable effect on the physical and chemical properties of soil, and hence on crop productivity. However, there are few reports on the long-term effects of alley cropping on soil properties; of those that are available, most are from IITA, the institution with the longest record of alley cropping research.

Kang et al. (1989) reported that, with the continuous addition of *Leucaena leucocephala* prunings, higher soil organic matter and nutrient status were maintained than when no prunings were added (*see* Table 14). Attah-Krah et al. (1985) showed that soil under alley cropping was higher in organic matter and nitrogen content than soil without trees. Yamoah et al. (1986b) compared the effect of *Cassia*, *Gliricidia* and *Flemingia* in alley cropping situations, and found that soil organic matter and nutrient status were maintained at higher levels with *Cassia*. Another set of reports from IITA by Lal (1989) showed that, over a period of six years (12 cropping periods), the relative rates of decline in the status of nitrogen, pH and exchangeable bases of the soil were much less under alley cropping than under

Table 14. Some chemical properties of the soil after six years of alley cropping maize and cowpea with *Leucaena leucocephala* at IITA, Nigeria

Treatment (kg/N/ha)	*Leucaena* prunings	pH-H_2O	Org. C (mg/kg)	Exchangeable cations (c mole/kg)		
				K	Ca	Mg
0	removed	6.0	6.5	0.19	2.90	0.35
0	retained	6.0	10.7	0.28	3.45	0.50
80	retained	5.8	11.9	0.26	2.80	0.45
LSD (0.05)		0.2	1.4	0.05	0.55	0.11

Source: Kang et al. (1989)

non-alley cropped (continuous cropping without trees) control plots (*see* Table 15). These studies also suggested the nutrient cycling possibilities of *L. leucocephala* hedgerows, as there was evidence of a slight increase in soil pH and exchangeable bases during the third and fourth years after the establishment of these hedgerows.

Table 15. Changes in soil nitrogen and organic carbon contents under different management systems at IITA, Nigeria

	1982		1986	
Treatment	**0-5 cm**	**5-10 cm**	**0-5 cm**	**5-10 cm**
Soil nitrogen (%)				
Plow-till	0.214	0.134	0.038	0.042
No-till	0.270	0.174	0.105	0.063
Leucaena — 4 m	0.397	0.188	0.103	0.090
Leucaena — 2 m	0.305	0.160	0.070	0.059
Gliricidia — 4 m	0.242	0.191	0.066	0.067
Gliricidia — 2 m	0.256	0.182	0.056	0.038
LSD (0.05)	0.01		0.01	
Organic carbon (%)				
Plow-till	1.70	1.12	0.42	0.28
No-till	2.50	1.41	1/08	0.52
Leucaena — 4 m	3.01	1.59	0.90	0.91
Leucaena — 2 m	2.35	1.10	0.71	0.65
Gliricidia — 4 m	2.26	1.53	0.63	0.60
Gliricidia — 2 m	2.38	1.47	0.62	0.61
LSD (0.05)	0.12		0.12	

Source: Lal (1989)

The soils in the IITA studies were relatively fertile alfisols. Studies on the long-term effect of alley cropping on soil fertility, carried out by Palm and Sanchez (1988) and Szott et al. (1989) on the acid oxisols and ultisols of the Peruvian Amazon basin, produced less promising results. This is probably because oxisols and ultisols are less able to supply subsoil nutrients to the tree component for recycling.

There appear to have been very few studies carried out on the effect of alley cropping on other soil properties. A study by Budelman (1989) near Abidjan in Côte d'Ivoire compared the effect of three mulches — *Flemingia macrophylla*, *Gliricidia sepium* and *Leucaena leucocephala* — applied at a rate of 5000 kg/ha dry matter. As shown in Table 16, all three, particularly *F. macrophylla*, had a favorable effect on soil temperature and moisture conservation. The report by Lal (1989), based on the IITA study, indicated lower soil bulk density and penetrometer resistance and higher soil moisture retention and available plant water capacity under alley cropping practices compared to non-alley cropping practices (*see* Table 17).

Although it seems clear from the numerous field projects being undertaken in various parts of the tropics that planting contour hedgerows is an effective soil conservation measure, only a few reports have been produced from these studies. Apart from the excellent review by Young (1989), which contains convincing arguments on the beneficial effect of agroforestry on soil conservation, two recent reports have been produced recently which are worth mentioning.

Table 16. Average temperature and soil moisture content over a 60-day period after adding three different mulches at a rate of 5000 kg/DM/ha

Treatment/ mulch material	No. of observations at 15.00 h	Average temperature at 5 cm (°C)	Average % soil moisture over 0-5 cm
Unmulched soil	40	37.1	4.8
Leucaena leucocephala	40	34.2 (-2.9) [1]	7.1 (+2.3) [1]
Gliricidia sepium	40	32.5 (-4.6)	8.7 (+3.9)
Flemingia macrophylla	40	30.5 (-6.6)	9.4 (+4.6)
LSD value [2]		1.20	1.84
Standard deviation		±0.47	±0.39

Note: 1. Between brackets — the difference relative to an unmulched soil
2. Average and standard deviation of the 10 series of observations
Source: Budelman (1989)

Table 17. Changes in some physical properties of soil under alley cropping and no-till systems at IITA, Nigeria

Cropping system	Infiltration rate at 120 min. (cm/hr) year 1	year 3	year 5	Bulk density (g/cc) year 1	year 3	year 4
Plow-till	24.2	23.2	21.4	1.36	1.51	1.42
No-till	18.0	12.4	5.0	1.30	1.47	1.62
Alley cropping						
Leucaena 4 m	39.8	13.0	22.2	1.26	1.44	1.50
Leucaena 2 m	13.6	22.4	22.8	1.40	1.39	1.65
Gliricidia 4 m	18.8	18.8	16.8	1.30	1.35	1.57
Gliricidia 2 m	13.8	21.0	19.61	1.33	1.45	1.55
LSD (0.1)		5.8			0.03	

Source: Lal (1989)

The first report, by Ghosh et al. (1989), is based on a study carried out in a 1700mm/yr rainfall zone in southern India. *Leucaena* and *Eucalyptus* were intercropped with cassava, groundnut and vegetables, and the *Leucaena* was pruned to 1 m at 60-day intervals after the first year. In the second year of the study, the estimated soil loss from the bare fallow plot was 11.94 t/ha/yr, whereas for the *Leucaena* and *Leucaena* + cassava plots the estimated loss was 5.15 t/ha/yr and 2.89 t/ha/yr, respectively.

The study by Lal (1989) conducted in Nigeria produced several significant results: the erosion from *Leucaena*-based plots and *Gliricidia*-based plots was 85% and 73% less, respectively, than in the case of the plow-tilled control plots; *Leucaena* contour-hedgerows planted 2 m apart were as effective as non-tilled plots in controling erosion and run-off; and there were significantly higher concentrations of bases in water run-off from alley cropped plots than from non-alley cropped plots, indicating the nutrient-cycling effect of the hedgerow perennials. This study also showed that, during the dry season, the hedgerows acted as windbreaks and reduced the desiccating effects of 'harmattan' winds, and that soil moisture content at 0-5 cm depth was generally higher near the hedgerows than in non-alley cropped plots.

Effect on crop yields

The criterion most widely used to assess the desirability of alley cropping is the effect of this practice on crop yields. Indeed, most alley cropping trials produce little data other than crop yield data, and these are usually derived from trials conducted over a relatively short period of time.

Many trials have produced promising results. An eight-year alley cropping trial conducted by Kang et al. (1989) in southern Nigeria on a sandy soil showed that, using *Leucaena* prunings only, maize yield could be maintained at a 'reasonable' level of 2 t/ha, as against .66 t/ha without *Leucaena* prunings and fertilizer (*see* Table 18). Supplementing the prunings with 80 kg N/ha increased the maize yield to over 3.0 t/ha. Unfortunately, the effect of using fertilizer without the addition of *Leucaena* prunings was not tested. Yamoah et al. (1986b) reported that, to increase the yield of maize alley cropped with *Cassia, Gliricidia* and *Flemingia congesta (macrophylla)*, it was necessary to add nitrogen. However, an earlier report by Kang et al. (1981) indicated that an application of 10 t/ha of fresh *Leucaena* prunings had the same effect on maize yield as the addition of 100 kg N/ha, although to obtain this amount of *Leucaena* leaf material it was necessary to supplement production from the hedgerows with externally grown materials.

Kang and Duguma (1985) showed that the maize yield obtained from using *Leucaena* leaf materials produced in hedgerows planted 4 m apart was the same as the yield obtained when 40 kg N/ha was applied to the crop. In a study conducted in the Philippines, O'Sullivan (1985) reported that when maize was intercropped with *Leucaena*, yields of 2.4 t/ha (with fertilizer) and 1.2 t/ha (without fertilizer) were obtained; the corresponding yields for maize grown without *Leucaena* were 2.1 and 0.5 t/ha. However, the experimental details of this study, such as quantity of fertilizer added and length of experiment, are not clear. In a study conducted by Watson and Laquihon (1985), also in the Philippines, maize yields of 1.3, 2.7, 3.7, 2.6 and 3.7 t/ha were obtained under no fertilizer, *Leucaena* hedgerows, *Leucaena* hedgerows + fertilizer, *Leucaena* prunings equivalent to fertilizer rate, and fertilizer-only treatments, respectively; the fertilizer rate was 100 kg N/ha and 50 kg P/ha.

Table 18. Grain yield of maize grown in rotation with cowpea under alley cropping at IITA, Nigeria (t/ha)

Treatment [1]	Year						
	1979	1980	1981 [2]	1982	1983	1984+	1986
oN-R	-	1.04	0.48	0.61	0.26	0.69	0.66
oN+R	2.15	1.91	1.21	2.10	1.91	1.99	2.10
80N+R	2.40	3.26	1.89	2.91	3.24	3.67	3.00
LSD (0.05)	0.36	0.31	0.29	0.44	0.41	0.50	0.18

Note: + Plots fallowed in 1985

1. N-rate 80 kg/N/ha; (-R) *Leucaena* prunings removed; (+R) *Leucaena* prunings retained. All plots received basal dressing of P, K, Mg and Zn
2. Maize crop affected by drought

Source: Kang et al. (1989)

Results from other alley cropping trials are less promising. For example, in trials conducted on an acid soil at Yurimaguas, Peru, the yields of all crops studied in the experiment, apart from cowpea, were extremely low, and the overall yield from alley cropped plots was equal to or less than that from the control plots (*see* Table 19). Rice grain yields in rotations 4 and 6 were significantly lower than those

Table 19. Grain yield and dry matter production from crops in different cropping systems at Yurimaguas, Peru

	Cropping system (kg/ha) [1]							
Cycle crop	**Cc**	**Ie**	**Nc**	**Fc**	**Ce**	**Ie**	**Nc**	**Fc**
	Grain [2]				Dry matter			
1. Corn	634a		390a	369a	1,762b		2,268b	4,339a
2. Cowpea	778ab	526b	1,064a	972ab	1,972b	1,791b	2,597b	4,766a
3. Rice	231a	211a	488a	393a	1,138b	1,160b	1,723b	3,718a
4. Rice	156c	205bc	386b	905a	929b	1,151b	2,121b	5,027a
5. Cowpea	415a	367a	527a	352a	1,398b	1,353b	1,404b	3,143a
6. Rice		386b	382b	1,557a		1,054b	1,037b	4,797a

Note: For grain or dry matter, means within a row that are followed by the same letter are not significantly different, based on results from the least significant difference test, p = 0.05

1. Cc = *Cajanus cajan* alley cropping; Ie = *Inga edulis* alley cropping; Nc = non-fertilized, non-mulched control; Fc = fertilized, non-mulched control
2. Corn grain yield based on 15.5% moisture content; rice and cowpea grain yields based on 14% moisture content. *Inga* plots in cycle 1 and *Cajanus* plots in cycle 6 were not cropped

Source: Szott (1987)

from the non-fertilized control plots; cowpea yields in rotations 2 and 5 were highest from the non-fertilized control plots. Szott (1987) concluded from these data that the main reasons for the comparatively poor crop performance under alley cropping treatments were root competition and shading. Other possible explanations are that the surface mulch physically impeded seedling emergence, that the decomposing mulch temporarily immobilized the nutrient cycle and thus seriously reduced the amount of nutrients avaiable to young seedlings at a critical stage of their growth, and that the inherent low levels of nutrients in the soil immobilized the 'recycling' mechanism by tree roots.

Other results suggest that alley cropping may not be effective under moisture-stressed conditions. In a four-year study carried out at the International Center for Research in the Semi-Arid Tropics (ICRISAT) near Hyderabad, India, hedgerow species outcompeted the crops when there was limited moisture, resulting in reduced crop yields (Corlett et al., 1989; ICRISAT, 1989; Ong et al., 1989; Rao et al., 1990). Similar observations have been reported from semi-arid areas in north-western Nigeria (Odigi et al., 1989) and in Kenya (Nair, 1987; ICRAF,1989; Kenya Forest Research Institute, unpubl.). A six-year study in north-western India showed that maize, black gram and cluster bean yields were lower when these crops were alley cropped with *Leucaena* hedgerows than when grown in pure stands (Mittal and Singh, 1989). The green fodder and fuelwood yields of *Leucaena* were also lower under alley cropping than under non-alley cropped hedgerows. However, it appears that, instead of returning the *Leucaena* prunings to the soil as green manure, they were taken away as fodder.

The IITA study by Lal (1989) referred to above showed that maize and cowpea yields were generally lower under alley cropping than when grown as sole crops (*see* Tables 20 and 21). A significant observation in this study was that, in the years when rainfall was below normal, yield decline was more drastic under closer-spaced alleys, indicating severe competition for moisture between the hedgerows and the crops. Recent studies at IITA by Ehui et al. (1990) have projected maize yields in relation to cumulative soil losses under different fallow management systems. As shown in Figure 3, when maize yields were adjusted to account for land in fallow and land occupied by hedgerows, the highest yields would be obtained if alleys were spaced 4 m apart, whereas the lowest yields would be obtained from 9-year-fallow treatments.

Table 20. Mean grain yield of maize grown under alley cropping over a six-year period at IITA, Nigeria

Sytem	Treatments		Maize grain yield (t/ha)					
	Perennial species	Spacing (m)	1982	1983	1984	1985	1986	1987
A	Plow-till	—	4.1	4.9	3.6	4.3	2.7	2.3
	No-till	—	4.0	4.1	4.0	5.0	2.4	2.7
B	*Leucaena*	4	3.7	3.3	3.7	4.8	2.1	2.0
	Leucaena	2	4.4	3.6	3.8	4.2	1.7	2.5
C	*Gliricidia*	4	3.9	3.9	3.6	4.5	2.6	2.2
	Gliricidia	2	3.8	3.2	3.3	4.8	1.6	2.8
Mean			4.0	3.8	3.7	4.6	2.2	2.4
LSD				(0.05)		(0.01)		
	(i) Systems (S)			0.27		0.22		
	(ii) Treatments (T)			0.34		028		
	(iii) Years (Y)			0.48		0.39		
	(iv) S x T			0.48		0.39		
	(v) T x Y			0.83		0.68		

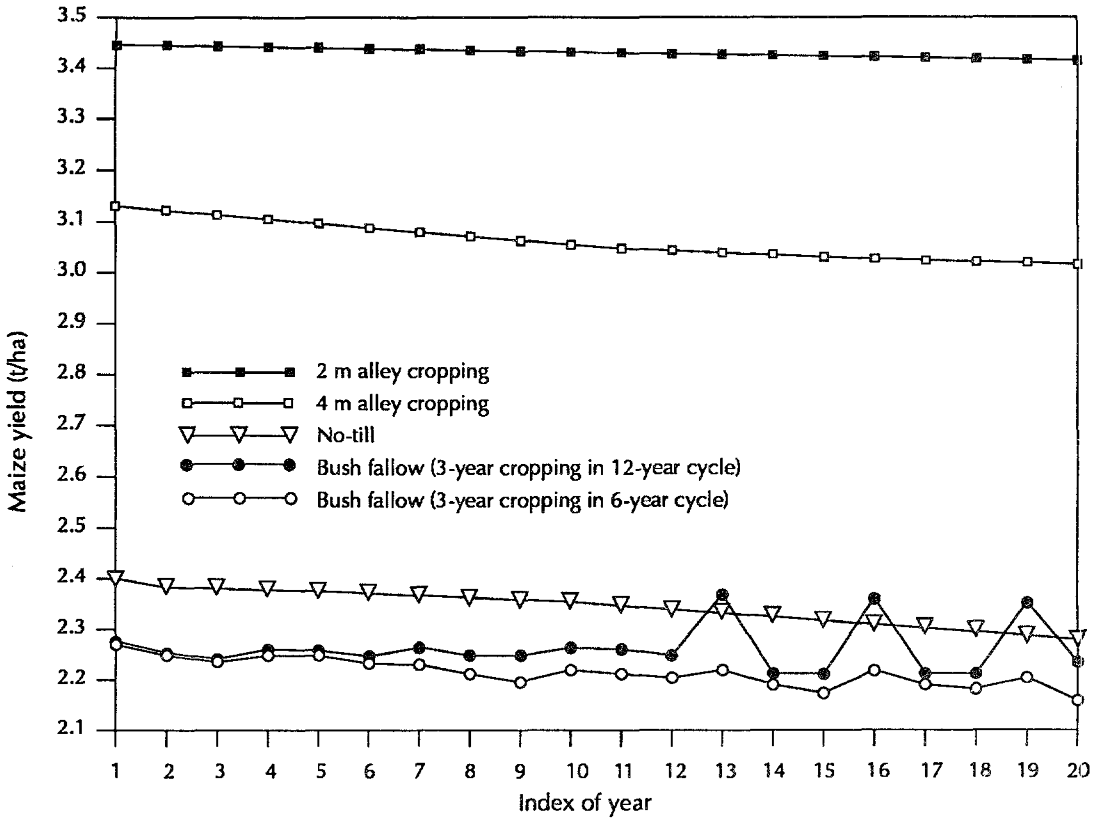
Source: Lal (1989)

Table 21. Mean grain yield of cowpea in a maize-cowpea rotation under alley cropping over a six-year period at IITA, Nigeria

System	Treatments		Cowpea grain yield (kg/ha)					
	Perennial species	Spacing (m)	1982	1983	1984	1985	1986	1987
A	Plow-till	—	720	442	447	435	992	369
	No-till	—	1520	829	1193	784	1000	213
B	*Leucaena*	4	1000	514	581	409	285	222
	Leucaena	2	730	319	503	159	146	236
C	*Gliricidia*	4	950	600	670	590	452	207
	Gliricidia	2	700	533	678	405	233	233
Mean			937	540	679	464	518	319
LSD				(0.05)		(0.10)		
	(i) Systems (S)			120		99		
	(ii) Treatments (T)			147		121		
	(iii) Years (Y)			208		171		
	(iv) S x T			208		171		
	(v) T x Y			361		297		

Source: Lal (1989)

Figure 3. Projected maize yield over a 20-year period under different land-management systems in south-western Nigeria



Source: Ehui et al. (1990)

Future directions

Many studies on alley cropping are now being undertaken in various parts of the tropics, and in the next few years there is likely to be a rapid increase in the amount of data available. As more data becomes available, so the interpretation of that data must become more refined and consistent. Many experts seem to have taken extreme positions in interpreting the results that have been produced so far, some going to great lengths to use the data to defend alley cropping, others to denigrate it. However, the above review of research results indicates clearly that the merits or demerits of alley cropping cannot be judged according to any single criterion or on the basis of short-term results. Benefits other than crop yield, such as soil fertility improvement and the yield of fuelwood and fodder, must be carefully weighed against drawbacks, such as labor requirements or pest management problems.

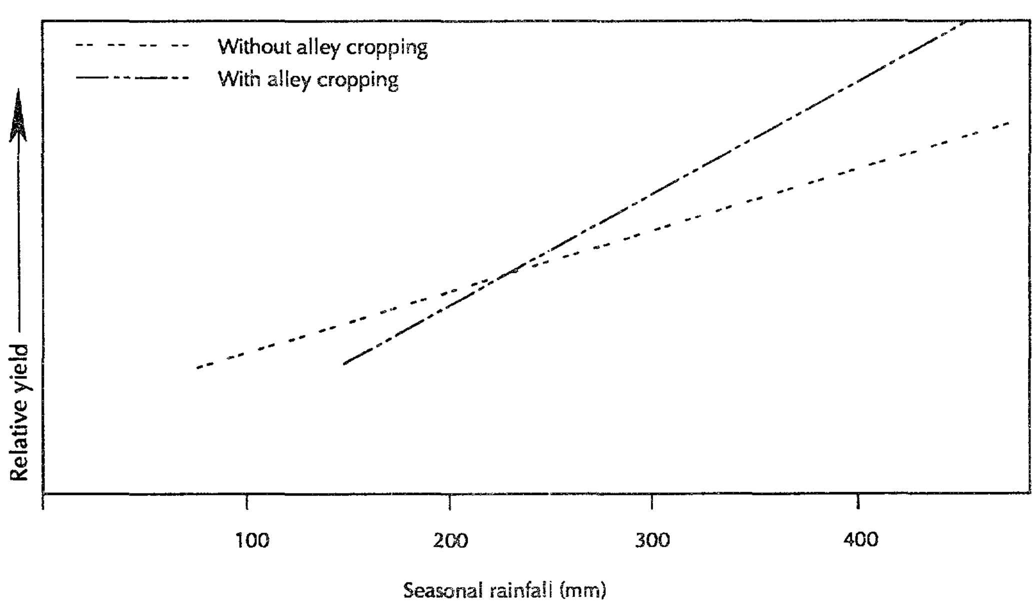
A key issue is ecological adaptability. Many research results suggest that although alley cropping offers considerable potential in the humid tropics, it is not a suitable crop production technology for the semi-arid tropics. The provision of nutrients through decomposing mulch, a basic feature of alley cropping, depends on the quantity of the mulch as well as on its quality and time of application. If the ecological conditions do not favor the production of sufficient quantities of mulch, then there is no perceptible advantage in using alley cropping on this score.

Let us look, for example, at the quantity that could potentially be produced from 1 ha, an area in which it is feasible to have 20 hedgerows of *Leucaena*, each 100 m long and planted 5 m apart. If the hedgerows are pruned three times per cropping season (once just before the season and twice during the season), and if the rainfall conditions permit two crops a year, there would be six prunings a year. Assuming that each meter of hedgrow produces 375 g of dry matter (1.5 kg fresh matter) from each pruning, the total biomass yield will be 4500 kg (derived from 375 g x 2000 m x 6 cuttings). If, on average, 3% of this dry matter consists of nitrogen, the total nitrogen yield could be 135 kg/ha/yr, about half of which can be expected to be 'lost' to current season crops. However, there are several factors which may limit the realization of this potential. A major factor is soil moisture. In most semi-arid regions, rainfall is unimodal and falls over a four-month period. Thus, the number of prunings would be reduced to a maximum of three. The mulch yield will also be lower, to the extent that the nitrogen yield will not be enough to produce any substantial nitrogen-related benefits for the crop. Added to this, there are the shade effects of the hedgerows, and the reduction of land available for crop production (20 hedgerows, each 1 m wide and 100 m long, will cover 2000 m^2 per hectare, or 25% of the total area). Furthermore, farmers may choose to remove the mulch for use as animal fodder, for example, rather than adding it to the soil, as is the case in Haiti (Bannister and Nair, 1990).

Because of such limitations, alley cropping as it is known today is unlikely to be widely adopted in the semi-arid tropics. This does not imply that agroforestry in general is unsuitable for these regions. Indeed, some of the best-known agroforestry systems are found in the semi-arid tropics — for example, the system based on *Acacia (Faidherbia) albida*, found in the dry areas of Africa (Felker, 1978; Miehe, 1986), and the system based on *Prosopis cineraria*, found in the dry areas of India (Mann and Saxena, 1980; Shankarnarayan et al., 1987).

A very generalized correlation between rainfall and alley cropping potential is presented in Figure 4. An important point to remember is that alley cropping can be appropriate for both low and high levels

Figure 4. A generalized picture of crop (maize) yield, with and without alley cropping, in relation to rainfall during the cropping season under semi-arid conditions



Source: Based on Coulson et al. (1989)

of productivity; if higher levels of crop productivity are the goal, fertilizer application is necessary under most conditions, and fertilizer-use efficiency can be substantially increased under alley cropping (Kang et al., 1989). In extremely acidic sandy soils, such as those in the Peruvian Amazon basin (Szott et al., 1989; TropSoils, 1988), the success of alley cropping depends on the extent to which external inputs such as fertilizers are used. The choice of hedgerow species that can adapt to harsh conditions is also an important management consideration under such circumstances.

Plantation Crop Combinations

Tropical perennial plantation crops occupy about 8% of the total arable area in developing countries. Some are not widely cultivated, and play a minor role in national economies; others produce high-value economic products for the international market and are therefore very important, economically and socially, to the countries that produce them. The focus of this review falls on the latter group, which includes oil-palm, rubber, coconut, cacao, coffee, tea, cashew and black pepper. Sisal and pineapple, although major crops, are not considered because they differ from the other crops in terms of growth habits and duration.

Smallholder applications

Traditionally, most of the major plantation crops were developed as monocultural production enterprises which required high labor input during harvesting and, in some cases, during processing. As a result, modern commercial plantations of crops such as rubber, oil-palm, coffee and tea are well-managed, profitable land-use enterprises in the tropics, supported by excellent research back-up. However, contrary to popular belief, substantial proportions of these crops are grown by smallholders (Ruthenberg, 1980; Nair, 1983; Watson, 1983; Nair, 1989).

Most of the cacao production in Ghana and Nigeria, for example, comes from smallholdings. The cacao is usually grown in association with a specific crop, such as maize, cassava, banana, cucumbers and sweet potato, especially during the first four years after planting the cacao. The size of the plantations varies widely from one smallholding to another. In Trinidad, cacao is mainly a forest species, grown under shade trees, with no fertilizer or pesticide application.

Many smallholder rubber plantations in South-East Asia and Nigeria are based on integrating rubber with a variety of crops, including soya bean, maize, banana, groundnut, fruit trees, pepper and coconuts. In Malaysia, poultry raising in rubber stands is also a common and remunerative practice (Ismail, 1986).

Among the notable examples of smallholder systems in which coffee is integrated with other crops and/or livestock are the banana and coffee smallholdings of Bukoba District, Tanzania; the coffee and maize holdings at Jimma in the Ethiopian highlands; the coffee and plantain systems on steeply sloping land in Colombia; and the coffee and diary milk production systems in Kenya.

Most of the coconut production in India, the Philippines, Sri Lanka and the Pacific islands comes from smallholdings in which the coconut crop is integrated with a large number of annual and perennial crops. In Sri Lanka and the Pacific islands, grazing under coconut is also common.

Cashew grows in a wide range of ecological situations, including wastelands where few other species thrive. In India, Tanzania and Mozambique, smallholders often grow cashew trees with other crops, planting the trees in a rather random way so that they appear scattered on the smallholding. Grazing under cashew is also very common, particularly on smallholdings in East African coastal areas.

Research results

Although research on these practices has been carried out since the 1970s, before agroforestry came of age, few results have been published. Most of the data that are available concern coconut-based systems in India (Nair, 1979; Nelliat and Bhat, 1979), Sri Lanka (Liyanage et al., 1984; Liyanage et al., 1989) and the Far East and the South Pacific (Plucknett, 1979; Smith, 1983; Smith and Whiteman, 1983; Steel and Whiteman, 1980).

The rationale for integrating coconut palm with other crops is that a number of shade-tolerant and economically useful species can be grown between or under coconut during different stages of growth of the coconut crop. The light reaching the understorey in coconut stands, apart from the period between the 8th and 25th year of the palm's growth, is enough to permit the growth of other compatible species. The palm's rooting pattern is such that most of the roots are near the bole, and thus there is minimal overlap between the palm's rooting system and that of other crops. Taking these factors into account, Nair (1979) proposed several possibilities of crop combinations with coconut palms of different age groups, and evaluated the performance of these combinations (*see* Figure 5).

Considerable research has also been done on coffee/shade tree and cacao/shade tree combinations, largely by CATIE in Costa Rica. Much of this research has concentrated on nutrient-related issues. A long-term replicated experiment, established in 1977 and known as 'La Montana', has produced a significant amount of data on such topics as organic matter, nutrient cycles, litter fall and water infiltration. The tree species used in this experiment are *Erythrina poeppigiana*, which is periodically cut back, and a valuable timber species, *Cordia alliodora*, which is periodically thinned (Alpizar, 1985; Alpizar et al., 1986; Fassbender et al., 1988; Heuveldop et al., 1988; Imbach et al., 1989). In a study comparing the two species, Beer (1987, 1989) showed that *E. poeppigiana*, when pruned twice or three times a year, can return the same amount of nutrients to the litter layer that are applied to coffee plantations via inorganic fertilizers, even at the highest recommended rates for Costa Rica (270 kg N/ha/yr, 60 kg P/ha/yr and 150 kg K/ha/yr). The annual nutrient return in this litter fall represents 90-100% of the nutrient store in the above-ground biomass of *E. poeppigiana*. In the case of *C. alliodora*, which is not pruned, nutrient storage in the tree stems, particularly of potassium, is a potential limiting factor to both crop and tree productivity. This suggests that, in fertilized plantations of cacao and coffee, litter productivity of shade trees is an important characteristic, even more important than nitrogen fixation.

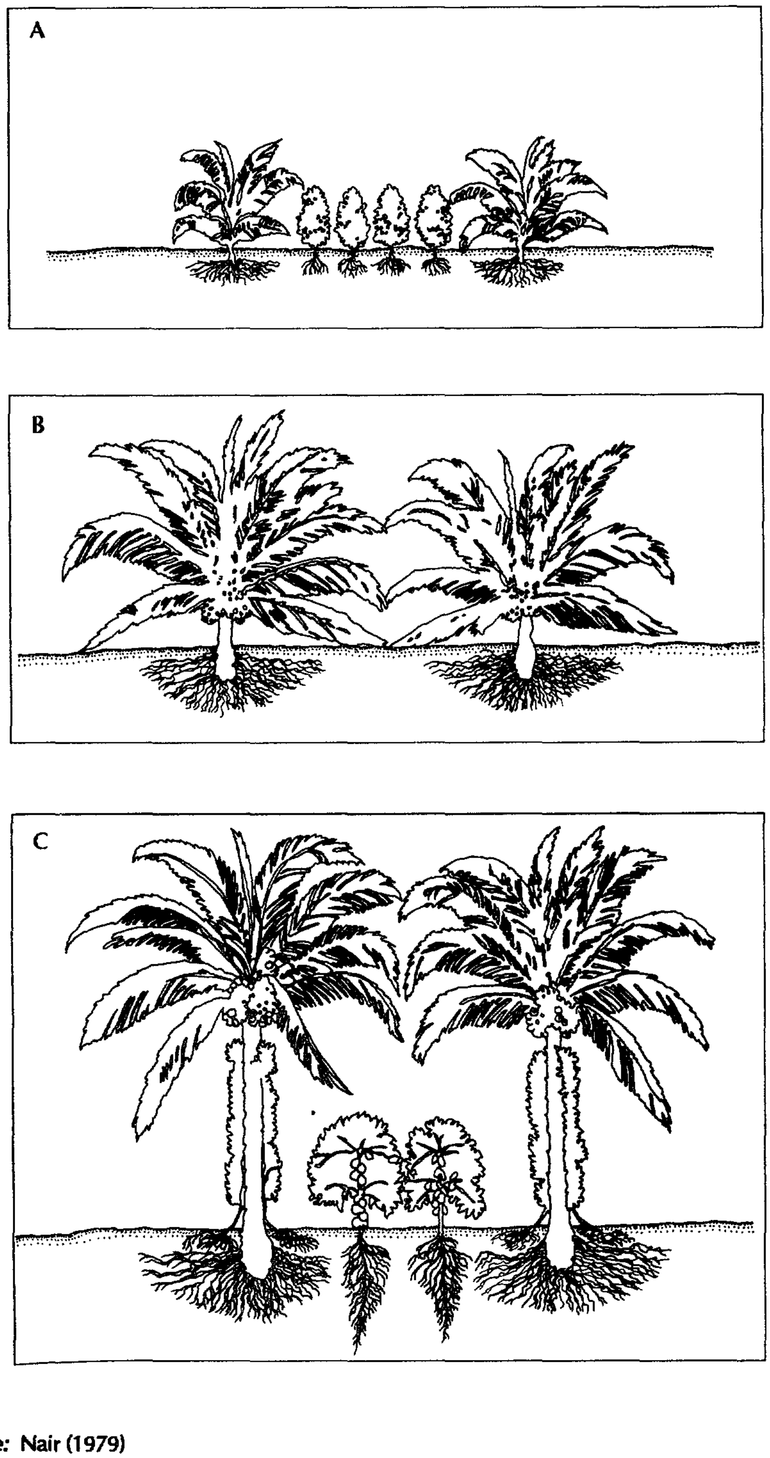
Among other plantation crop combinations that have been described are: crops grown with cashew and coconut on the Kenyan coast (Warui, 1980); crops grown with plantation crops in north-eastern Brazil (Johnson and Nair, 1984) and in Bahia, Brazil (Alvim and Nair, 1985); crops grown with babassu palm in Brazil (May et al., 1985); crop associations with arecanut palm in India (Bavappa et al., 1982); and crop associations with oil-palm and rubber in West Africa (Watson, 1983). Most of these are qualitative and analytical descriptions of existing systems, and thus do not contain quantitative data based on research investigations.

Windbreaks and Shelterbelts

Farmers throughout Africa use windbreaks to protect crops, water sources, soils and settlements. Hedgerows of *Euphorbia tirucalli* protect maize fields and settlements in the dry savannas of Tanzania and Kenya. Tall rows of *Casuarina* line thousands of canals and irrigated fields in Egypt. In Chad and Niger, multispecies shelterbelts protect wide expanses of cropland from desertification. These practices are not new, but the design of multipurpose windbreaks for smallholdings will require new agroforestry skills.

Figure 5. Schematic presentation of the growth phases of coconut palm indicating possibilities for crop combinations

A Early phase, up to about 8 years: canopy develops gradually; much scope for intercropping
B Middle phase, about 8-25 years: greater ground coverage by canopy: little scope for intercropping
C Later phase, after about 25 years: increased scope for intercropping; a multistorey combination of coconut, cacao and black pepper is depicted



Source: Nair (1979)

The protective and productive benefits of windbreaks at a given site depend upon the distance between windbreaks, the species used, and other site-specific management practices; the value of the subsidiary products should also be taken into account. Before planting windbreaks, however, the benefits must be weighed against direct costs, such as labor and planting materials, and other disadvantages such as the amount of land windbreaks will take up that would otherwise be used for crop production, and the competition between crops and windbreak species for water, light and nutrients. The benefits, in terms of increased crop yields, soil improvements and economic by-products, must outweigh the costs.

Design and content

The distance between windbreaks is determined mainly by the height of the tallest trees in the row. A properly designed windbreak can protect a field at least 10 times as long as the height of the tallest trees. The protective influence will diminish with distance from the windbreak. A more permeable windbreak will shelter a longer stretch of cropland than a dense windbreak.

The most effective windbreaks provide a semi-permeable barrier to wind over their full height. Since their shapes change as they grow, it is usually necessary to mix several species of different growth rates, shapes and sizes in three or more rows. Some fast-growing species, such as *Eucalyptus*, *Cassia*, *Prosopis*, *Leucaena* and *Casuarina*, should be used to establish the desired effect as rapidly as possible. However, no tree will grow rapidly if it is not well adapted to the environmental conditions of the site. In addition, some of these species are not as long-lived as slower-growing trees. Fast- and slow-growing species should be mixed to extend the useful life of the windbreak. Mixing species also provides protection against attack from diseases or pests that can easily destroy single-species stands.

Diversifying the species in a windbreak brings a wider variety of products for local users. A fully developed windbreak can yield wood, fruit, fodder, fiber and honey for sale and home use. Where animals are allowed to graze nearby, some of the lower, outer trees or shrubs should be unpalatable; for example, the leaves of neem, *Azadirachta indica*, are unpalatable, and this species has been used in Niger to protect windbreaks from livestock damage. Fodder species should be grown near the center or along an inside edge, where they are not exposed to animals but can be cut by hand.

Species should be used selectively, even those that have been used widely in windreaks. *Eucalyptus* should not be planted alone as it has a sparse understorey and may have an adverse effect on water availability and crop productivity in the vicinity. *Azadirachta indica* is known to shade crops and thus reduce the land available for crop production. Successful windbreaks have incorporated such unlikely trees as cashew and indigenous *Acacia*. The species selected must fit together as a group into the overall design; this design, in turn, must suit the local landscape and land-use system.

While diversity is important, the choice of species must also take into account the growth form, size and growth rate required to establish an effective windbreak, as well as the production priorities of the local people. Environmental hazards such as insect pests (especially termites), wild and domestic animals, poor soil and drought will narrow this choice. Water management, especially during establishment, will be important, particularly in dry environments; microcatchments, hand watering or irrigation should be planned.

Anticipated benefits

Although very little information is available on the quantities of wood produced from trees growing in windbreaks for use as fuelwood, poles and other purposes, some preliminary results are encouraging.

In windbreak tests in the Majjia Valley in Niger, which has favorable soils and a mean annual precipitation of 425 mm, the average yield of usable firewood from *Azadirachta indica* was 5 kg per year. Based on these calculations, two rows of trees, each 100 m long and with the trees in each row spaced 4 m apart, would provide 250 kg of fuelwood (5 kg x 25 trees x 2 rows), or enough to cater for the needs of a family of five for almost two months. This windbreak would protect about 1 ha of cropland. If extended to protect 6 ha, the windbreak would produce enough fuelwood to meet the family's annual requirements. It should be noted, however, that the wood cannot be harvested until several years after planting.

Cashew trees used in a windbreak in Senegal are yielding a fair amount of fruit and nuts. Although not in sufficient quality and quantity to be commercially viable on a large scale, these by-products are an important addition to local diets. *Acacia scorpioides* trees planted in windbreaks in Niger are now producing seed pods used for traditional leather tanning. As there is a steady market for this product, the windbreaks make a modest but important contribution to the local economy. In other cases where *Prosopis* species are used in windbreaks, seed pods are collected daily to supplement livestock feed and some are sold in the local markets. In north-western China, shelterbelts of *Paulownia* have been planted to stop desert encroachment. A 21-55% decrease in wind speed was measured in the protected area, together with an increase of 12.5% in air humidity and 19.4% in soil humidity (in the top 50 cm). Maximum summer and winter temperatures were reduced, crop yields increased and wood was produced.

The reported effects of windbreaks on crop yields vary considerably. In some cases grain yields have increased significantly, in others the competition for water and light, the land 'lost' to the tree planting or changes in the microclimate have slightly reduced crop yield. The effect on yield clearly depends to a large extent on the design of the windbreak, the particular crop involved and the environment. Because of this, the multiple tree products and long-term soil conservation should be considered as the primary benefits. In the Sahel, alhough statistically valid results are still not available, it appears that millet and sorghum yields in fields protected by windbreaks of *Azadirachta indica* can be as much as 23% higher than in unprotected fields nearby (Bognettean-Verlinden, 1980). In a year with poor rainfall, even relatively small differences in crop yields can be significant for the local population. It was estimated that pollarding these windbreaks every four years would bring Majjia Valley residents US$ 800 worth of construction poles and wood per kilometer of windbreak (USAID, 1987).

Other Agroforestry Practices

A large number of other agroforestry systems have been reported from different parts of the developing world. Nair (1989) describes some 25 systems, and several others have been described in various publications, notably the work by Rocheleau et al. (1988).

Some research has been conducted on the group of systems which includes homegardens and multistorey tree gardens. Good analyses of homegardens have been produced by Soemarwoto (1987), Fernandes and Nair (1986), Ovalle et al. (1990) and Alvarez-Buylla Roces et al. (1989). Michon et al. (1986) and Okafor and Fernandes (1986) have described the multistorey tree gardens of Indonesia and Nigeria, respectively. Another widespread group consists of the various types of silvopastoral systems.

In this review, the lack of a detailed examination of these two groups of systems is in no way intended to belittle their importance or potential for improvement. Rather, it is because there is, as yet, little scientific information to draw on. This applies to many other systems which, although they have been in existence for a long time, have received little or no scientific attention. What scientific material is available shows the merits of these indigenous systems and points to several possibilities for improvement. As pointed out in a recent ICRAF document (ICRAF, 1990), agroforestry appears to have considerable potential to solve land-use problems in a wide variety of environments and socio-economic conditions, but much of this potential needs to be tested, confirmed and further developed. It is time to move on from simply adding to the speculative literature on agroforestry's potential to conducting detailed research into all aspects of agroforestry which will provide scientifically sound bases for improving the vast array of existing systems.

AGROFORESTRY APPROACHES FOR AFRICA

The need for detailed research on agroforestry systems is nowhere more urgent than in Africa, a continent in crisis. To quote from *The Greening of Africa* by Harrison (1989), 'agroforestry is arguably the single most important discipline for the future of sustainable development in Africa.'

The per capita agricultural output increase of 1.8% per annum is far outpaced by the continent's population growth rate of 3.1% per annum. Almost 90% of Africa's population (360 million in 1980) consists of rural-based subsistence farming families whose sole sources of energy are fuelwood and charcoal. The rate of destruction of closed forest to meet their needs was estimated at 1.3 million ha annually between 1976 and 1980; the rate of destruction of open forest (savanna woodland) between 1981 and 1985 was estimated 2.3 million ha annually. The fragile environment, characterized by low and unpredictable rainfall in the extensive semi-arid areas, poor soils, high soil-surface temperatures, strong winds and a variety of pests and diseases aggravates the problems of food scarcity and dwindling forests. Shifting cultivation and livestock herding, the bases of subsistence farming in much of sub-Saharan Africa, are no longer efficient and rational forms of land-use management. Africa's agricultural and environmental crisis is the theme of many recent publications, such as that produced by the Office of Technology Assessment (1988).

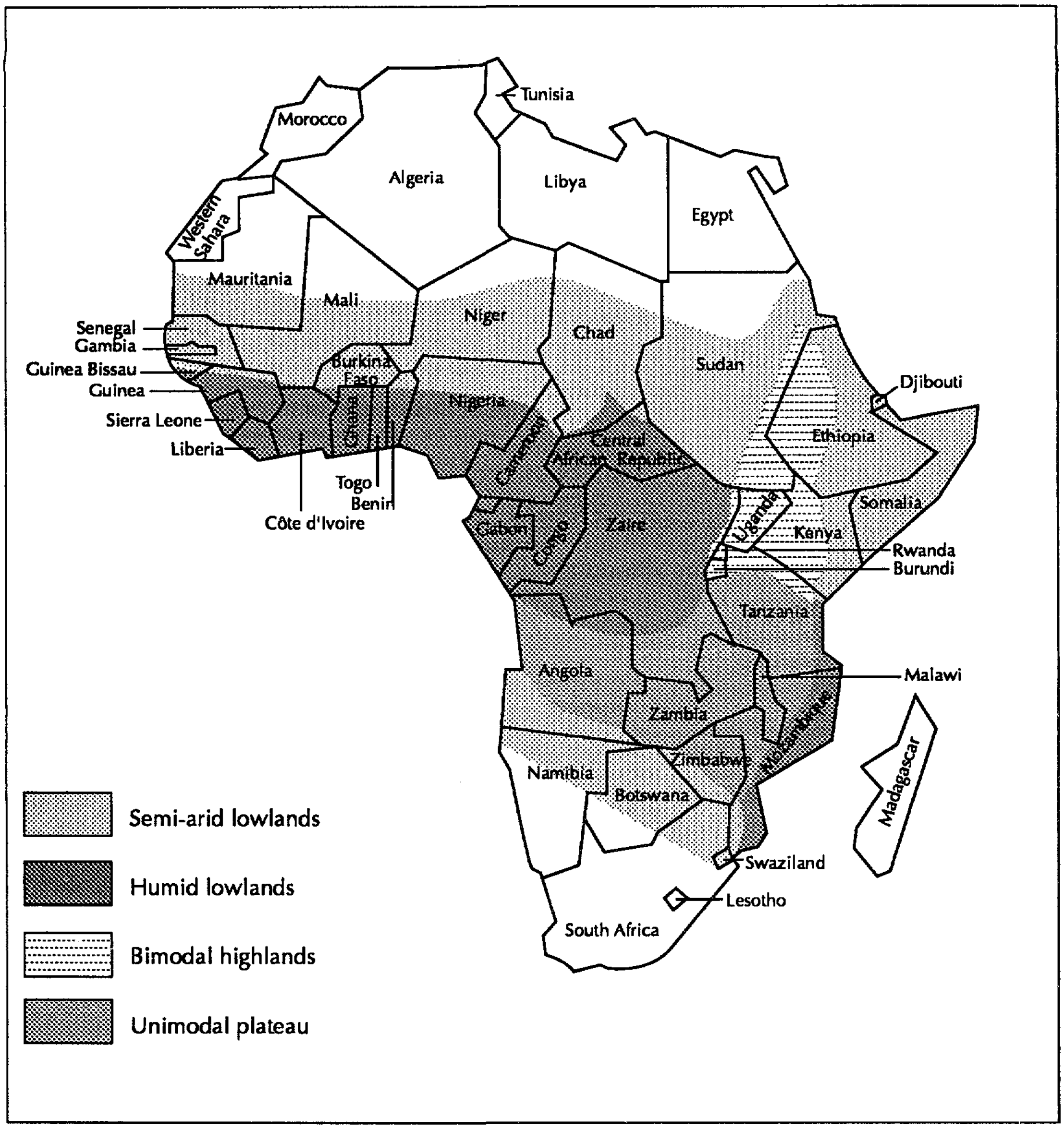
Agroforestry is now widely considered to be a sound approach to address some of Africa's land-use problems. However, the problems are so enormous and the conditions so varied that there can be no uniform set of agroforestry practices for different regions. Quite a lot of information is available on the continent's indigenous agroforestry systems and on the multipurpose trees and shrubs used in these systems (von Maydell, 1986, 1987). What is needed now is to develop improved agroforestry practices for specific regions, making the best use of this information.

Ecozone Approach to Agroforestry Design

An ecological approach could be the basis for developing appropriate agroforestry designs. ICRAF's approach in setting up the Agroforestry Research Networks for Africa (AFRENAs) is based on such a strategy (ICRAF, 1987; Torres, 1987). ICRAF has distinguished four broadly homogeneous ecozones in sub-Saharan Africa: the unimodal upland plateau of southern Africa; the bimodal highlands of eastern and central Africa; the semi-arid lowlands of West Africa (the Sahelian zone); and the humid lowlands of West Africa (*see* Figure 6). A multidisciplinary team at ICRAF has developed a methodology to identify and diagnose the land-use systems and constraints in each ecozone, and then to identify specific constraints which can be addressed by agroforestry and on which research efforts should focus (Raintree, 1987).

Multipurpose trees scattered on croplands and pastures, woodlots and boundary plantings containing multipurpose trees for fodder and fuelwood, and improvements to taungya systems are technologies

Figure 6. Four ecozones of Africa for agroforestry project design



Source: ICRAF (1987), Torres (1987)

that can be applied in all ecozones, with modifications. Based on the available information on indigenous systems, the agro-ecological analysis of the spread of these systems and the characteristics of major agroforestry practices, certain groups of practices can be suggested for each ecozone.

Upland plateau of southern Africa	Fuel/fodder woodlots; soil conservation technologies; buffer-zone agroforestry
Highlands of eastern and central Africa	Alley cropping; soil conservation technologies; homegardens; plantation crop combinations (coffee, tea)
Semi-arid lowlands of West Africa	Fuelwood lots; silvopastoral systems and protein banks; windbreaks and shelterbelts
Humid lowlands of West Africa	Alley cropping; improved fallow; multistorey tree gardens; plantation crop combinations; homegardens

These represent broad technology packages. In designing the technical details of these packages, various social issues will come into play.

Two issues which are particularly important in the context of agroforestry development for Africa, which are applicable to all ecozones and which have not been discussed elsewhere in this review, are buffer-zone agroforestry and the use of indigenous trees and knowledge.

Buffer-Zone Agroforestry

The introduction of agroforestry practices into buffer zones around protected forest areas has been suggested as a technology option which may not only reduce pressures on forest resources but also improve the living standards of the rural population living around these protected areas (van Orsdol, 1987).

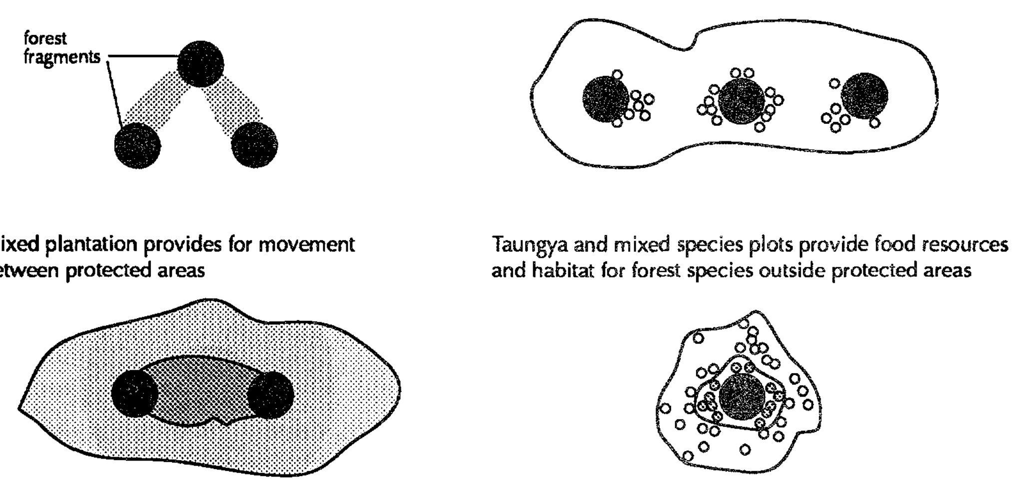
The buffer-zone system, first put forward by UNESCO (1984), consists of a series of concentric areas around a protected core; usually, this core area has been designated as a national park, wilderness area or forest reserve, and its biological diversity is maintained through careful management. Around this core area is a primary buffer zone in which research, training, education and tourism are the main activities. This primary buffer zone is surrounded by secondary or transitional buffer zones, in which sustainable use of resources by the local community is permitted. It is in these transitional zones that great possibilities exist for agroforestry innovations.

The buffer-zone concept is based mainly on the need to protect pristine forest systems from the effects of human encroachment, the main objective being to maintain the biodiversity within the ecosystem. Therefore, in most buffer-zone systems there is a wooded zone around the core forest (Oldfield, 1988). In some of these systems, some human activity, such as selective logging, is allowed in this wooded zone (Johns, 1985). Another approach is to allow agricultural activities to be carried out up to the edge of the core area; this creates an 'edge effect' that may have a negative impact on the primary forest (Janzen, 1983). To overcome problems arising from the conflict between the need to preserve pristine forest systems and the need to produce food for growing populations, Eisenburg and Harris (1987) suggested a mixed land-use pattern in which there are increasing levels of human exploitation: a pristine core area, surrounded by a selectively logged forest, which, in turn, is surrounded by a mixed farming area which could incorporate agroforestry practices. Although this is similar to the UNESCO model, the design of buffer zones for an integrated management or agroforestry project cannot always incorporate the double buffer-zone system of the UNESCO model. In practice, alternative designs that take local conditions into account may be more effective (for example, buffer zones composed of both semi-wild and agricultural areas can be used as a buffer against human encroachment on protected areas).

There are several possible agroforestry schemes for buffer-zone management. Some models suggested by van Orsdol (1987) are given in Figure 7. Mixed plantations, or woodlots of mixed, indigenous tree species can provide less hostile environments for forest animals. Taungya systems could be used to gradually expand small forest tracts while minmizing the social and economic hardships to the surrounding population caused by limited resource availability. The concept of buffer-zone agroforestry is being successfully implemented in a number of projects, including the Bururi Forest Project in Burundi (USAID, 1987), the Uganda Village Forest Project (CARE, 1986) and the Conservation of Oku Mountain Project in Cameroon (MacLeod, 1987; van Orsdol, 1987). In all these projects, an important factor is the inclusion of useful indigenous trees in the system designs.

On the institutional front, buffer-zone agroforestry requires a multidisciplinary approach. This will bridge the gap between the various organizations which have traditionally tackled Africa's development problems within the framework of single disciplines.

Figure 7. Some models of buffer-zone agroforestry schemes



Mixed plantation provides for movement between protected areas

Taungya and mixed species plots provide food resources and habitat for forest species outside protected areas

Bush fallow techniques in areas of low population pressure with low utilization in corridors surrounding forest fragments with heavier use in surrounding transition buffer zone

Phasing out taungya near forest allows for natural regeneration and expansion of the forest habitat

Source: van Orsdol (1987)

Use of Under-Exploited Species and Indigenous Knowledge

Tropical forestry and forest management has focused almost entirely on timber production options. Even in agroforestry systems, wood production is seen as the primary function of tree components. However, in addition to this function, trees and natural forests provide many other products, such as food, fiber, medicinal products, oils and gums, which play a critical role in meeting the basic needs of indigenous populations (*see* Table 22). The methods of collecting, processing and using these tree products are location-specific. Moreover, many of these products, the plants that produce them and the processes which are involved preparing them for use are little known outside the areas in which they occur.

Becker (1984) analyzed the food production potential from indigenous trees and shrubs in the Turkana and Samburu regions of Kenya and the Farlo region in Senegal. She estimated that the annual harvestable production of leaves and fruits amounted to about 150 kg/ha in the Saharo-Sahel, 300 kg/ha in the typical Sahel, and 600 kg/ha in the Sudano-Sahel. This corresponds with the general rule, based on various observations in the Sahel, that in 'normal' ecosystems the annual increment of non-woody biomass from trees, shrubs and palms in kg/ha roughly equals the rainfall in mm. Results from East and West Africa indicate that about 15% of that biomass can be classified as edible. Thus, in the above-mentioned ecological zones, 23, 45 and 90 kg, respectively, of edible material would be

Table 22. Some examples of indigenous multipurpose trees used as food sources in Africa

Class	Tree species	Major uses
Main food	*Treculia africana*	Edible fruit, kernels, fuel, pulp for paper industry
	Parkia biglobosa	Edible seed, fodder, timber, fuel, fertility drug
Food supplement	*Garcinia cola*	Edible seed, chew sticks, snake repellent
	Afzelia africana	Fermented leaf as vegetable
Condiments	*Xylopia aethiopica*	Tobacco substitute, timber, fuel
	Monodora myristica	Nutmeg substitute
Leafy vegetable	*Pterocarpus milbraedii*	Edible leaf, dye, camwood
	Pterocarpus santalinoides	Edible leaf, fodder, boundary line
	Pterocarpus soyauxii	Edible leaf, timber, religious purposes
Fats/oils	*Elaeis guineensis*	Oil, wine, thatch, mulch
	Butyrospermum paradoxum	Kernel oil, edible fruit
Fruits	*Spondias mombin*	Fruit, jam, jelly, fodder
	Vitex doniana	Fruit, fuel, timber
Jams/jelly	*Chrysophyllum albidum*	Fruits, tools, religious purposes
Drinks	*Raphia hookerii*	Wine, mats, raffia, piassava
Masticatory	*Raphia nitida*	Chew sticks, fodder, fence
Fodder	*Moringa oleifera*	Edible flowers and leaves
	Canarium schweinfurthii	Edible leaves and fruits

available per hectare annually. Correlating these figures with an average population density of 1 person per square kilometer, and assuming a ratio of 4:1 for leaves and fruits, between 450 and 1,800 kg of edible fruits from trees and shrubs could be available per person (between 1.25 and 5.0 kg fruit per adult daily). However, fruits and other edible materials are not available throughout the year.

A study on the baobab tree, *Adansonia digitata*, in Farlo, Senegal showed that, on average, there were 5.5 trees per person in a representative region. The leaves of the tree are rich in nutrients (100 g of fresh leaves contain 23 g dry matter, 3.8 g crude protein, 700 mg calcium and 50 mg ascorbic acid), and are used extensively as a green-leaf vegetable. Even more valuable is the fruit pulp, which is rich in vitamins B-1 and C; the flour produced from the dried fruits contains up to 48% protein and 2% vitamin B-1 on a dry weight basis.

The food production potential of the woody perennials in the agricultural and pastoral areas in Africa's dry regions has been little studied. The only available report is by Becker (1983), who identified 800 species of wild plants with human-nutrition potential in the Sahel. However, there are some reports from other regions on the food production potential of these species (Ogle and Grivetti, 1985; Okafor, 1981; FAO, 1983). Most of these species are used as a source of food only at times of emergency, such as drought, when preferred species are scarce.

The exploitation of these food-producing indigenous trees and shrubs and of the indigenous knowledge concerning their production and processing has wide implications, not only in terms of food security, but also with regard to the conservation and use of genetic resources to meet current and future needs.

Developing appropriate technologies for each of the ecozones is a complex task. Many issues, ranging from the species to be used and their arrangement and management to socio-economic evaluations, need to be addressed before recommending even prototype technologies. It is heartening to see that some technologies, such as alley cropping, are receiving systematic attention through such organizations as the Alley Farming Network for Africa (AFNETA) (Attah-Krah, 1989). However, alley cropping seems to be receiving most of the attention of agroforestry experts and scientists, at the expense of other time-tested indigenous technologies.

Chapter 4

Economic and Socio-Cultural Issues

ECONOMIC CONSIDERATIONS

Economists argue that economic considerations will be the prime factor in deciding the usefulness of agroforestry to the land user. Obviously, traditional agroforestry systems have proved economically beneficial to the communities that have developed them. In other words, they have passed the 'economic test'. However, the land-use problems facing tropical countries are such that not only must new agroforestry technologies pass this test, but also that the test itself must be more rigorous.

There are two major difficulties in realistically assessing the economic advantages of agroforestry systems. First, more attention has been paid to the particular problems which gave rise to various tree-based practices than to the practices themselves; thus, we tend to be more concerned with developing new or improved land-use practices to cope with such issues as fuelwood shortages, than with increasing our understanding of the economic contributions of such practices. Second, as a result of this approach, only a few systems or practices have been subjected to this kind of economic evaluation. Even when such evaluations are done, most of them are carried out before the implementation of a project *(ex ante)*, rather than after the project has produced field data *(ex post)*. It is likely that at least some of the assumptions on which *ex ante* analyses are based may prove incorrect when tested in the field.

Evaluation Criteria

Any objective assessment of agroforestry's impact on the farmer must examine both the economic benefits and the costs. The analysis by Arnold (1987) of the positive and negative economic features of agroforestry is particularly relevant here (*see* Table 23).

The methods of carrying out such analyses have been reviewed by a number of experts. Hoekstra (1985, 1990) provides a detailed examination of the issues or obstacles that economists encounter, as well as the options that are available to them, in the appraisal of agroforestry projects. Magrath (1984) discusses the particular evaluation problems involved in agroforestry and provides a valuable survey of economic returns on agroforestry projects. Other important works in this field include those by Filius (1982), Arnold (1984), Betters (1988) and Prinsley (1990). Linear programming is now being adopted as a useful tool in economic evaluations of agroforestry. The multi-component multi-period budgeting (MULBUD) approach which was developed by ICRAF (Etherington and Mathews, 1983) provides a practical, microcomputer-based tool for economic evaluations, but it is based on various assumptions.

Table 23. Main benefits and costs of agroforestry

Benefits and opportunities	**Costs and constraints**
Maintains or increases site productivity through nutrient recycling and soil protection, at low capital and labor costs	Reduces output of staple food crops where trees compete for use of arable land and/or depress crop yields through shade, root competition or allelopathic interactions
Increases the value of output from a given area of land through spatial or temporal intercropping of tree and other species	Incompatibility of trees with agricultural practices such as free grazing, burning, common fields, etc., which make it difficult to protect trees
Diversifies the range of outputs from a given area, in order to (a) increase self-sufficiency, and/or (b) reduce the risk to income from adverse climatic, biological or market impacts on particular crops	Trees can impede cultivation of monocrops and introduction of mechanization, and thus (a) increase labor costs in situations where the latter is appropriate and/or (b) inhibit advances in farming practices
Spreads the needs for labor inputs more evenly throughout the year, so reducing the effects of sharp peaks and troughs in activity, characteristic of tropical agriculture	Where the planting season is very restricted, e.g. in arid and semi-arid conditions, demands on available labor for crop establishment may prevent tree planting
Provides productive applications for under-utilized land, labor or capital	The relatively long production period of trees delays returns beyond what may be tenable for poor farmers, and increases the risks to them associated with insecurity of tenure
Creates capital stocks available to meet intermittent costs or unforeseen contingencies	

Source: Arnold (1987)

As noted earlier, the non-monetary and indirect benefits of agroforestry are often cited as part of the justification for developing or improving agroforestry systems. However, economic assessments of such benefits have not been attempted. Given that sustainability issues are now receiving a lot of scientific attention in relation to all forms of land-use, including agroforestry, it is likely that improved or modified evaluation criteria for assessing these non-monetary and indirect benefits on a long-term basis will soon be evolved and widely used.

Economic Analyses of Agroforestry Projects

One of the difficulties in reviewing economic analyses of agroforestry is that there is a tendency to apply the term 'agroforestry' to many types of existing or potential farming systems, ranging from 'pure' agriculture to 'pure' forestry. An appraisal of World Bank funding for agroforestry projects refers to many 'grey areas' that fall between agroforestry and traditional forestry (Spears, 1987). In a review of economic studies in agroforestry, Jickling (1989) found that some of the best studies relate to small on-farm tree plantings or woodlots, which are only peripherally relevant to agroforestry; he pointed out, however, that although these studies tend to isolate tree-planting investments from other on-farm agricultural activities, they are nonetheless valuable in assessing the positive returns from tree production in the context of the overall farm budget.

Economic studies on 'farm forestry' projects include the following: an economic and financial analysis of a project on smallholder tree plantations in the Philippines (Gregersen and Contreras, 1979); case studies from eight countries on the economics of tree farming for fuelwood production

(Energy/Development International, 1986); an *ex ante* economic analysis of a farm forestry project in northern Nigeria (Anderson, 1987); and an *ex ante* study comparing the Kenya fuelstick project with a conventional woodlot project (Hosier, 1987).

There have also been several studies on more clearly defined agroforestry systems. Once again, most of them have focused on alley cropping.

Alley cropping

The review of alley farming by Kang et al. (1989) discusses the results of some economic assessments of the practice. In his analysis of the IITA alley cropping experiments, Ngambeki (1985) reported that managing the *Leucaena leucocephala* trees increased the labor requirement by about 50% compared with non-alley cropped plots; however, this extra labor cost was offset by the increase (up to 60%) in maize yield under alley cropping and lower fertilizer costs. An earlier report by Ngambeki and Wilson (1984) on these IITA experiments was reviewed in Kang et al. (1989); it showed that 31 person-days of labor were needed for the initial pruning and leaf stripping of *L. leucocephala* trees growing on 1 ha of land at a density of 15 x 10^3/ha; the labor requirement dropped to about 20 person-days for pruning and leaf stripping during the two cropping seasons. In the following year, initial pruning took only 16 person-days. However, it needs to be pointed out that the relatively high labor requirement in the first year did not discount for fallow clearing, a major component in traditional systems.

An additional advantage of alley cropping is the reduced labor requirement for clearing fallow land for cultivation. A survey carried out by the International Livestock Center for Africa (ILCA) in a savanna area infested with *Imperata cylindrica* showed that the labor required to clear fallow regrowth from the alley farm was 47% less than that required by an adjacent traditional farm (ILCA, 1987). A similar study in an area where *I. cylindrica* was not a problem showed an advantage of 18% for the alley farm. Farmers have also commented that weed control is easier between alleys (Ngambeki and Wilson, 1984).

Working in southern Nigeria, Sumberg et al. (1987) developed an economic model to compare maize production in monocropping situations with production when maize was alley cropped with *Leucaena leucocephala*. They concluded that alley cropping was more profitable, but that the advantage decreased as the price of maize increased relative to the cost of labor. Labor requirements for prunings were estimated at 18 days/ha, which is high compared to the ILCA (1987) data. However, profitability is more sensitive to maize prices than to labor costs. The model assumed that the tree foliage yield would be 3 t/ha and that the mulch would be laid on the surface rather than incorporated into the soil.

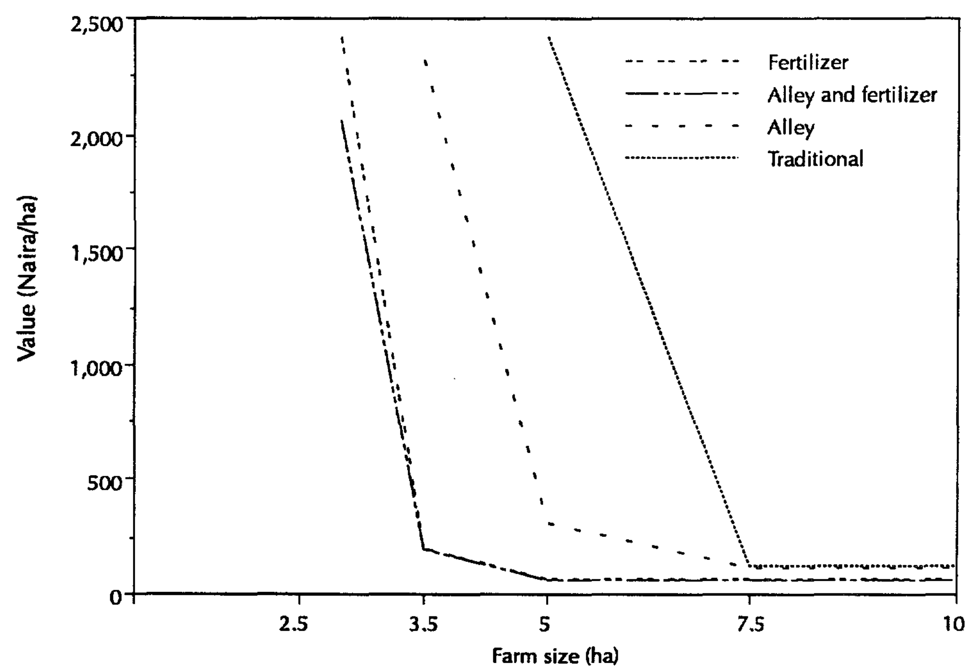
Verinumbe et al. (1984), using a linear programming model, reported that *Leucaena*-maize alley cropping was economically attractive. More labor was required to prune trees, but lower amounts of fertilizer and herbicide were needed. The authors concluded that under severe cash constraints, and where hired labor was available at a relatively low cost, a *Leucaena*-maize alley cropping system was the most promising package. A similar conclusion was reached by Raintree and Turray (1980) in a study using a linear programming model of an upland rice-*Leucaena* system.

In the IITA alley cropping experiments, Ehui et al. (1990) used a capital budgeting approach to determine the profitability of alley cropping in comparison with traditional shifting cultivation, taking into account the short- and long-term impact of soil erosion on agricultural productivity in south-western Nigeria. The systems included: two continuous cultivation, alley cropping systems with *Leucaena* at 2 m and 4 m inter-hedgerow spacings; a continuous cultivation, no-till farming system; and two traditional bush fallow systems with a 3-year cropping cycle followed by 3 and 9 years of fallow. Under a 10% discount rate, when no yield penalties are imposed (in the case of low population density), the 9-year fallow + 3-year cropping system was the most profitable, followed by the 4 m alley cropping, no-till, 2 m alley cropping and 3-year fallow + 3-year cropping systems. However, when yield penalties are imposed on yields because land is taken out of cultivation for the fallow cycles (in the case of high population and rising land values), the 4 m alley cropping system is the most profitable, followed by the no-till, 2 m alley cropping, and the 12- and 6-year cycles of bush fallow systems. Thus where access to new forest land is 'costless', traditional bush fallow systems with longer fallows are advantageous, but where there are heavy population pressures and land is scarce, the 4 m alley cropping system seems to be the most desirable option.

In another recent study using a linear programming model for farming systems in south-western Nigeria, Ashraf (1990) found that alley cropping would increase the length of the cropping cycle in a bush fallow system with cacao when the farm size was less than 5 ha. Thus, alley cropping could contribute to transforming a shifting cultivation system into a semi-permanent cultivation system, especially in the case of smallholdings. The study showed that a higher degree of land-use intensity can also be obtained by using chemical fertilizers, the best results being obtained when alley cropping is combined with fertilizer application (*see* Figure 8). However, it seems likely that where population pressure on land is not severe and/or fertilizers are easily available, farmers may consider that the high cost of labor makes alley cropping an unattractive option.

The relationship between fertilizer availability and alley cropping has also been stressed by Walker (1987). He argues that in India, fertilizer use is more attractive than sacrificing land to trees to obtain mulch; furthermore, fallowing is no longer a common practice in most parts of India. However, these arguments ignore important soil-productivity attributes of alley cropping.

Figure 8. Projected shadow prices of fallow land for farms of various sizes under different management systems in south-western Nigeria



Source: Ashraf (1990)

In summary, the available economic studies of alley cropping suggest that it is suited to humid and subhumid regions, but is less feasible in areas with high labor cost, low rainfall and/or long dry spells between rainy seasons. In addition, moderate levels of fertilization are necessary to get the best results from alley cropping.

Other agroforestry practices

Few detailed economic studies have been conducted on other agroforestry practices. Some of the descriptions of agroforestry systems contain quantitative economic data on labor requirements (Nair, 1989) and the various agroforestry project documents prepared by ICRAF contain *ex ante* economic analyses.

Among the practices on which economic studies have been conducted are:

Live-fencing and intercropping	Reiche (1987, 1988) summarized *ex post* economic analyses of *Gliricida* live-fences compared with dead-post fencing in Honduras and Costa Rica
Intercropping and silvopastoral systems	Some *ex ante* and *ex post* analyses have been reported from India (Mathur et al., 1984; Gupta, 1982; Shekhawat et al., 1988)
Multistorey cropping and plantation crop combinations	Some farm management and economic data on issues such as labor utilization, cost of cultivation and cost/benefit relations have been reported from coconut-based agroforestry systems in India (Nair, 1979)
Homegardens	Arnold (1987) reviewed the reported results of economic studies on homegardens in India, Indonesia and Nigeria.

A limitation of most of these economic analyses is that they are based on research station results and/ or certain assumptions. The assumptions could prove incorrect, and research station conditions differ from field conditions. Secondly, there is the question of evaluation of benefits. No matter how convincingly biological scientists argue in favor of agroforestry in terms of its long-term benefits, such as increased organic matter content, these attributes will remain 'invisible' to the economists until they can be translated into lower unit costs of production, visibly increased productivity, or some cost-saving differences in a social sense (Walker, pers. comm.). Finally, many studies focus on a commodity's long-term benefits, and do not pay adequate attention to the interim, short-term benefits. For example, returns from wood products harvested later than five years after planting the trees are considered, whereas returns from the regular harvests of small branches for fuel and fodder carried out before the final harvest are ignored.

As economic studies become more rigorous, such drawbacks will be rectified and more refined data will become available.

Adoption of Agroforestry Systems

How farmers perceive the costs and benefits of growing trees on their farms will determine whether or not they adopt agroforestry systems. This issue is dealt with by Arnold (1987) in his analysis of the results of economic studies on well-established homegardens in Java, eastern Nigeria and Kerala in

Table 24. Economic factors affecting adoption of agrofrestry practices in selected situations

Agroforestry systems	Constraints/opportunities	Farmer response	Contribution of agroforestry
Homegardens, Java	Declining landholding size, minimal or no rice paddy, minimal capital	Increase food and income output from homegardens	Highest returns for land from increasing labor inputs, flexibility of outputs in the face of changing needs and opportunities
	Further fall in landholding size below level able to meet basic food needs	Transfer labor to off-farm employment	Most productive and stable use of land with reduced labor inputs
Compound farms, Nigeria	Declining landholding size and site productivity, minimal capital	Concentrate resources in compound area, increase income-producing component and off-farm employment	Improves productivity, highest returns from labor, flexibility
Homegardens, Kenya	Declining landholding size, minimal capital	Bring fallow land into use intensify homegarden management	Multipurpose trees maintain site productivity and contribute to food and income
	Capital inputs substantially increased	Transfer land use to high-value cash crops, substitute fertilizer and herbicide for mulch and shade	Trees removed unless they are high-value cash crop producers
Farm woodlots, Kenya	Farm size below basic-needs level, minimal capital, growing labor shortage	Low-input low-management pole cash crops, off-farm employment	Lower capital input than alternative crops and higher returns from labor
Farm woodlots, Philippines	Abundant land, limited labor	Put land under pulpwood crop	Expands area under cultivation, increases returns from family labor

Source: Arnold (1987)

India. Table 24, which summarizes this analysis, indicates the main economic factors that encouraged farmers to incorporate tree/crop/livestock practices into their overall farming system. In most of the situations studied, farmers lacked access to capital and thus were unable to increase their land or labor resources by renting or purchasing. In many instances, farmer decisions were also clearly influenced by considerations of risk management.

Where there are limited resources and high susceptibility to risk, five overlapping farmer strategies involving the adoption of the improved practices can be discerned:

- To maintain the productivity of the land in situations of scarce capital, where trees can help substitute for purchased inputs of fertilizer and herbicide and for investments in soil and crop protection;

- To make productive use of the land in situations of scarce capital and labor, where trees, as low-input, low-intensity management crops, can make the most effective use of these resources;

- To increase useable biomass outputs per unit of land area in situations of scarce capital and limited land, where tree/crop/livestock combinations permit fuller use of available labor than other land uses;
- To increase income-earning opportunities from use of farm resources, where land productivity and/or the size of the landholding fall below the level at which the household's basic needs can be met from on-farm production;
- To strengthen risk management through diversification of outputs, wider seasonal spread of inputs and outputs, and build-up of tree stocks which can be sold to meet periodic or unforeseen needs for capital.

Such an interpretation of the economic role of agroforestry practices highlights a number of factors which are of relevance to the analysis, design and promotion of agroforestry systems.

In summary, research on the economics of agroforestry has been carried out on a rather ad hoc basis and consists mainly of *ex ante* analyses, based on assumptions, rather than *ex post* analyses based on field data. This is largely because not enough data have yet been produced from on-farm and on-station experiements. Inadequate attention has been paid to the economic value of short-term outputs such as fodder, green manure and small timber and to analyzing the economic returns from soil fertility improvement under agroforestry systems. However, the limited evidence that is available shows that while there are some situations in which agroforestry might not have economic advantages, there are many others in which the economic benefits are clear.

SOCIO-CULTURAL CONSIDERATIONS

The social acceptability of agroforestry is influenced by biophysical, socio-economic and cultural factors. In a recent analysis of this issue, Hoskins (1987) highlighted several factors that must be considered if new agroforestry practices are to be adopted by farmers. Foremost among these are land tenure, labor availability and the marketability of tree products. In addition, the way in which agrofroestry technologies are transferred to farmers must be adapted to suit the particular social contexts within which these farmers live.

Land Tenure

There is less likelihood that long-term agricultural strategies will be adopted in areas where land tenure systems do not guarantee continued ownership and control of land. As Francis (1989) states, the incentive for investing in soil-fertility improvement for future use of the land is low unless the benefits accrue to the tree planter. For example, at a site in south-eastern Nigeria, communal control of land rotation and seasonal redistribution of communally held land were identified as negative factors in the adoption of alley cropping (Francis and Atta-Krah, 1989). In certain parts of Africa, land tenure rules forbid the planting of trees (Osemebo, 1987). The annotated bibliography by Fortmann and Riddell (1985) lists several publications which focus on the issue of land tenure and agroforestry.

Rights over land are often distinct from rights over trees (Fortmann, 1985). Tree tenure issues include the right to own or inherit trees, the right to plant trees, the right to use trees and tree products and the right to dispose of tree products (Fortmann, 1988). These various rights differ widely across cultural zones and have a major influence on the social acceptability of agroforestry initiatives. In places where planting a tree may give the planter rights over the land on which it is planted, as in Lesotho

(Duncan, 1960) and Nigeria (Meek, 1970), for example, people with temporary claims to land may not be able to adopt agroforestry practices.

Social acceptability of agroforestry is also closely linked with the economic feasibility of the system. In a survey of 300 rural farmers in 32 settlements in Bendel State in Nigeria, Osemebo (1987) concluded that although prospects were high for the integration of tree planting into the traditional farming system, social acceptability relied heavily on cost-sharing devices between government and rural farmers, the availability of an active extension service and the potential of some direct economic output from the trees in the system. Farmers in the survey indicated that they were willing to plant trees if tree seedlings could be obtained at no cost, if intercropping trees with crops did not reduce crop yields and if there was some possibiity of earning income from the trees themselves. In the humid and savanna zones of Nigeria, it has been shown that, given a supply of seeds and adequate extension guidance, farmers will adopt alley cropping practices without requesting any form of credit or direct financial support (Okali and Sumberg, 1985).

Labor Requirements

Almost all agroforestry innovations demand changes in labor patterns, and labor requirement is always a factor which rural people take into consideration when deciding whether or not to adopt a new practice (Hoskins, 1987). Farm families have developed labor strategies based on using the inputs of most members of the family at various times of the year for different tasks. Obviously, additional labor for persons already fully occupied at peak labor seasons is considered more costly than additional demands during a slack season. For example, alley cropping is a labor-intensive practice and the costs of production increase considerably if additional labor has to be hired (Hoekstra, 1987). Although these additional costs will be offset by increased benefits, the immediate need for additional labor could be a disincentive to the adoption of the practice (Kang et al., 1989). This also explains the significance of farm size in Ashraf's analysis of the economics of alley cropping (Ashraf, 1990).

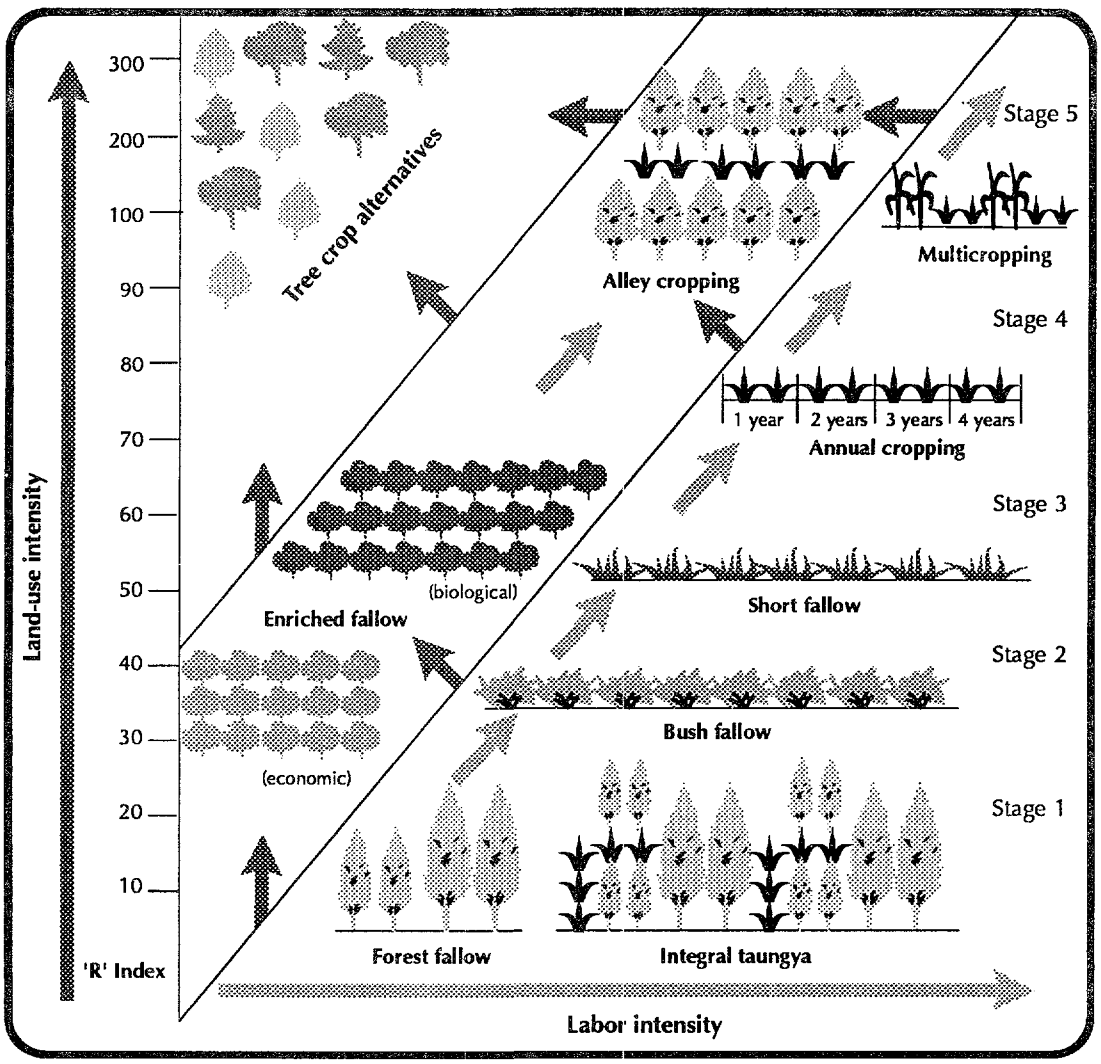
Labor peaks and patterns are important issues. If one compares the labor pattern in block planting (as in farm forestry, for example) and mechanized large-scale cash-crop planting, while it is clear this pattern greatly reduces labor costs, in the latter case this is considered desirable whereas for small-holders or landless workers who depend on farm labor income it is a serious disadvantage. In densely populated areas where labor is assumed to be in abundant supply, there are distinct labor peaks that coincide with the sowing and harvesting seasons of principal crops. Agroforestry systems could have the advantage of helping to spread the use of labor supplied by members of a farming family more evenly throughout the year, as Nair (1979) reported with reference to coconut-based agroforestry systems in India. Labor intensity is one of the main deciding factors in moving from traditional shifting cultivation practices to intensive agroforestry systems, as illustrated in Figure 9 (Raintree, 1986; Raintree and Warner, 1986).

Marketability of Tree Products

Direct and immediate income from a land-use system is a central issue in determining the social acceptability of that system. The processing and/or sale of agricultural commodities, and the rural industries based on these commodities, are essential sources of off-farm income for many farming societies. Recent studies of small-scale forest-based enterprises indicate that, in a number of countries studied, these enterprises are among the top three employers of rural people, especially resource-poor and landless people. Studies carried out by FAO (1987) have shown that the major constraints affecting the viability of such enterprises are poor access to markets and raw materials and inadequate

Figure 9. Agroforestry pathways for intensification of shifting cultivation

The land-use intensity factor R = C/(C + F) expressed as a percentage, where C and F are the lengths of cropping and fallow periods in the shifting cultivation cycle; R is also equivalent to the percentage of land in cultivation



Source: Raintree (1986), Raintree and Warner (1986)

organizational and management skills. Studies such as these indicate that effective rural development through agroforestry is possible if policies supporting the establishment of appropriate market infrastructures and the development of the necessary skills are implemented (Hoskins, 1987).

In many farming communities, products from trees on farms are usually considered a free commodity. Creating and expanding marketing opportunities for these 'free goods' will also mean making appropriate alternate provisions for meeting the local needs for locally produced and freely available products such as tannins, essential oils and medicines. With reference to wood products in particular (Hoskins, 1987), there is little understanding of the point at which the cost to the farmer of cutting of natural vegetation will be equal to or greater than the cost of producing and managing small or non-industrial wood sources for local use or sale. A number of development projects have been oriented around the sale of fuelwood or poles. Many of them are based on the assumption that if people are faced with a shortage of fuelwood, for example, they will purchase it, whereas, in practice, it is more likely that they will turn to alternative materials, such as agricultural by-products and biomass, for fuel. The results of some of these projects could therefore be economically disappointing. This could also happen in the case of large-scale popularization of new commodities, where there has been inadequate research on the uses and marketing of these commodities.

The Social Context

The best measure of the social success of new or improved technologies is the readiness with which farmers accept them. If innovations do not take account of the social context in which smallholders operate, then the potential of such innovations will not be realized (Chowdhry, 1985). Francis and Atta-Krah (1989) found that while the number of farmers who adopted alley cropping technologies increased from about 60 in 1987 to over 200 in 1989 in an on-farm research project site in south-western Nigeria, the adoption rate in a similar project in south-eastern Nigeria was considerably lower. The reasons for this lower adoption rate were low soil fertility and high acidity levels, incompatibility between the woody species tested and established cropping patterns and crop-rotation practices, the division of labor, decision-making processes within the household, and land and tree tenure rules. This suggests that if the extension efforts used to transfer the technology in the first project had been modified to take account not only of the different agro-ecological conditions but also of the different social patterns, a higher rate of adoption might have been achieved. Bannister and Nair (1990) reported similar situations from Haiti where, with minimum but suitably modified extension efforts, farmers willingly accepted contour hedgerow planting for soil conservation.

There is now a considerable amount of information on the design of agroforestry practices to suit particular farming conditions and particular social and political contexts (Raintree and Hoskins, 1988). The next crucial step is to collate this information and incorporate it into the training of those responsible for transferring new or improved agroforestry practices. This involves developing technology-testing methods which can be easily understood and used by farmers in their own environments, and emphasizing the need for strong links between the technology transfer agents and the farmers so as to ensure effective feedback from the farmers to the researchers.

As new agroforestry techniques move into farmers' fields, overall development issues will also become increasingly important, and the need for in-depth analyses of these issues will become more apparent. As suggested by Lundgren (1987), policies need to be designed which support agroforestry as an integral part of better land-use planning and which strengthen smallholders' access to new techniques. This applies not only to the wastelands and denuded hillsides created by defective land-use practices, but also to the prime lands that are soon likely to become wastelands if farmers continue to use poorly designed monocultural production systems.

Chapter 5

Agroforestry in the 1990s and Beyond

EMERGING TRENDS IN AGROFORESTRY

The establishment of ICRAF in 1977 marked the institutionalization of agroforestry. In 1987, the Council marked its 10th anniversary with the publication of *Agroforestry: A Decade of Development* (Steppler and Nair, 1987), which contains authoritative and encouraging reviews of the development of many aspects of agroforestry in the preceding deacade. As we move into the 1990s, the issues surrounding this new discipline and the direction in which it is going are becoming clearer. The initial euphoria has died down and the rush to define agroforestry and provide it with a conceptual framework has abated. Development agencies have accepted it as an important, fundable activity.

However, scientists contine to express concern about the lack of scientific data to support widely held assumptions on the advantages of agroforestry and the inadequate methodologies currently being used in agroforestry research. Extension workers are caught between policy makers' directives and the enthusiasm of the farmers to adopt agroforestry, on the one hand, and the absence of tested and proven technologies on the other.

The emerging trends in agroforestry can be identified by reviewing the following areas of activity: development-oriented projects; research projects; and education and training.

Development-Oriented Projects

It has been estimated that, between 1978 and 1987, World Bank lending for agroforestry projects was US $750 million (Spears, 1987). This represents a rise from 6% to 37% of total forestry investment by the Bank. Although many projects included in the survey are peripheral to agroforestry, the figures nevertheless give some idea of the amount of money being spent supposedly on agroforestry projects. Several other international and bilateral development-assistance institutions have also embarked upon large-scale projects in which agroforestry forms the main or one of the significant components.

The objectives in most of these projects include one or more of the following:

- soil productivity improvement (soil fertility, conservation)
- reclamation of degraded lands (eroded lands, hill slopes, salt-affected soils, alkaline/acidic soils)
- fuelwood production (boundary planting on farms, wasteland development)

- development of silvopastoral systems (grazing under trees, fodder banks)
- exploitation of indigenous tree species, especially fruit trees
- environmental protection (windbreaks and shelterbelts, microclimate amelioration)

The awareness of agroforestry as a potentially useful land-use approach in the tropics has grown so dramatically over the past 10 or 15 years that there are now very few land-use related development projects that do not contain a significant agroforestry component. However, the successful implementation of many of these projects is hampered by weaknesses in agroforestry research.

Research Projects

In contrast to the development-oriented projects, the situation regarding donor interest and funds for research in agroforestry is rather unsatisfactory. Until recently, agroforestry development enthusiasts saw little need for research, with the result that many projects currently under way were planned and implemented without proper research back-up. In addition to these funding problems, agroforestry research has been hampered by two major constraints — lack of trained personnel, and lack of appropriate methodologies and clear objectives. However, these constraints can be overcome if adequate funding becomes available.

Funding will be necessary to provide the opportunities for experts from various disciplines to work together on specific agroforestry projects, which will open up tremendous possibilities. A good example of the benefits of a multidiscipinary approach is the development by the United Nations University of an Agroforestry Expert System (Warkentin et al., 1990). This microcomputer-based system is the first attempt to apply the Expert System, already widely used in other areas, to agroforestry. At present, the system is being used to addresses the options for alley cropping. The user feeds quantitative information on site conditions (amount and distribution of rainfall, elevation, slope, soil texture, soil fertility level and soil reaction) into the program which then, on the basis of this information, makes recommendations on appropriate alley cropping possibilities. The program allows a choice of five hedgerow species and three hedgerow spacings; it will also indicate the degree of success that could be expected when implementing any of these recommendations. Although, in its present form, the program has many limitations, there is clearly immense potential for improvement by adding more parameters and broadening the choices.

This example of what could be accomplished by a multidisciplinary approach also serves to emphasize the point that the scope of agroforestry research should extend beyond the usual topics — multipurpose trees, nutrient cycling, socio-economic aspects, experimental designs, soil and plant management, and so on — to encompass modern methods of collating, storing and using knowledge. Technology transfer agents and land users should be able to obtain information without always having to consult the experts.

The need to formulate of a clear set of research objectives has begun to be recognized by a number of institutions and organizations. ICRAF, the leading international agency for promoting research in agroforestry, has recently produced a document entitled *Strategy 2000*, which reviews the Council's accomplishments and sets forth a strategy for achieving its stated goals and objectives by the year 2000 (ICRAF, 1990). The Council's overall objective is to 'strengthen the capacity of national and regional institutions in developing countries to develop appropriate agroforestry technologies, while undertaking pertinent strategic research with its own resources'. Inherent in this objective is an international approach. Other leading agroforestry institutions, such as CATIE in Costa Rica, and national research projects, such as the All-India Coordinated Research Project on Agroforestry, have developed strategies which have a regional or national focus, and research-oriented networks such as the Alley-Farming Network in Africa (AFNETA) and the NFTA are developing strategies which reflect their particular mandates and the needs of their members.

Clearly, then, despite various constraints, there are some important developments taking place in agroforestry rseearch. But some important questions remain. Are current efforts adequate? What is being done to build up a basic, rather than applied, research capacity? What measures are needed to promote a multidisciplinary research approach? As Lundgren (1987, 1989) has pointed out, the lack of an institutional niche for agroforestry is a serious drawback. In most national and international institutions agroforestry is an 'appendage' to forestry or agriculture, and these institutions are still run on conventional disciplinary lines, with the result that interdisciplinary activities such as agroforestry are given low priority. Fortunately, with the growing need to tackle environmental issues that cut across long-established disciplinary boundaries, this compartmentalization is steadily, albeit very slowly, breaking down. A very welcome development is the decision by the Consultative Group on International Agricultural Research (CGIAR) to bring agroforestry research into the CGIAR system and to establish the institutional mechanisms necessary to implement this decision.

Education and Training

Recognition of the need for organized research in agroforestry is a recent development; even more recent is the recognition of serious deficiencies in agroforestry education and training. Concern has been expressed about a number of issues, such as the lack of serious attention being paid to established land-use practices, the fact that current educational opportunities are too specialized, and the need for people to be trained at various levels to conduct research, implement development projects, undertake extension work, and so on. In addition, there is as yet no organized curriculum in agroforestry, nor a uniform approach to educational program development.

At an international workshop held at the University of Florida in 1988, these issues were discussed and various recommendations were made (Nair et al., 1990). Further discussions were held at an international symposium at Washington State University in 1989. General guidelines for program development in agroforestry education are now available, but the implementation of these recommendations is hampered by a lack of financial support. Many people from developing countries are being sent for training and education in agroforestry to institutions in various developed countries, but these institutions are themselves inadequately equipped and organized to provide such education and training. Donor agencies must be made aware of the need to support agroforestry education and training in these institutions so that, ultimately, knowledge can be transferred back to where it is needed most, in the developing countries.

SUSTAINABILITY

Sustainability is now a major issue in all development activities concerned with land management (Edwards et al., 1990). It is a concept that serves as a rallying theme for environmentalists and agricultural scientists, incorporates the short-term needs of the world's poor with the long-term concerns of society, and is changing the direction of international development efforts (Thomas, 1989).

However, although much has been written and said about sustainability, it still lacks a universally accepted definition. The following abstract attempts to explain why arriving at such a definition is so difficult: 'Sustainability is increasingly viewed as a desired goal of development and environmental management. This term has been used in numerous disciplines and in a variety of contexts. The meaning is dependent on the context in which it is applied and on whether its use is based on a social, economic or ecological perspective. Sustainability may be defined broadly or narrowly, but a useful definition must specify explicitly the context as well as the temporal and spatial scales being considered' (BIFAD, 1990).

Sustainability, like agroforestry, can be better explained by looking at the issues underlying the concept, rather than by relying on abstract definitions. In simple production-oriented systems, sustainability can be considered as the maintenance of production over time, without degradation of the natural base on which that production is dependent. Since sustainability deals with the long-term productivity of a system, there are three main issues to be considered: productivity changes over time, the time-frame in question, and the cost (ecological, social, economic and/or agronomic) associated with maintaining productivity.

The concept of sustainability was a cornerstone of agroforestry well before it attained its current prominence in land-use disciplines in general (Nair, 1989). It is inherent in many of the soil-productivity and socio-economic benefits of agroforesty. Soil productivity factors have been discussed at some length in earlier sections; the socio-economic characteristics of agroforestry which are relevant to the issue of sustainability are summarized in Table 24.

There is as yet no quantitative measure of sustainability, but several approaches are being discussed. One is to calculate the total factor productivity (TFP) of the system over a defined period of time (which could be the sum of the TFPs of individual components). Until such measurements are fully developed and widely used, we will have to contend with qualitative statements about agroforestry and sustainability. In the meantime, however, the value of agroforestry in terms of sustainability has been almost universally accepted.

FUTURE PROSPECTS

In a paper presented at an international conference on agroforestry in Edinburgh, United Kingdom in 1989, Nair (1990) painted the likely scenario of the use of agroforestry practices, worldwide, in the not-too-distant future:

- Serpentine hedgerows of *Leucaena*, *Gliricidia* and other fast-growing multipurpose trees and shrubs, opening the way for the Haitian farmer to once again grow maize and sorghum on soils which have been conserved and enriched by the hedgerows;
- Coffee grown on small farms under the shade of *Cordia alliodora* or between regularly pruned *Erythrina poeppigiana* in the highlands of Costa Rica, or under macadamia trees on the hillsides of Guatemala, and cacao grown under or between widely spaced rubber trees, coconuts and peach palms in the humid lowlands of Brazil and South-East Asia, giving the farmers additional cash income and economic stability;
- Fast-growing trees, grown with crops and along plot boundaries, providing fuelwood and fodder in semi-arid Africa and reducing the African woman's burden of searching for cooking fuel;
- Long and well-established rows of *Prosopis*, *Parkinsonia*, *Acacia* and other drought-hardy trees in sub-Saharan Africa, providing fuelwood and fodder to farmers and preventing desertification;
- Blocks of species such as *Acacia*, *Casuarina* and *Prosopis* planted on vast stretches of salt-affected soils in north-western India, reclaiming those once-productive lands for field crop agriculture;

- Traditional multispecies, multistoried homegardens, improved by regulated plant canopy architecture and species management, providing South and South-East Asian households with a wider range of products and at a faster rate;
- Improved fodder trees and regulated cattle stocking rates in traditional silvopastoral areas of Latin America and Africa, providing better returns and long-term sustainability;
- Trees planted on embankments and in catchment areas, providing fodder and fuel and stabilizing the watersheds in formerly degraded hilly areas in countries such as Nepal, Rwanda and Honduras;
- Improved fallow management systems, ranging from the use of fast-growing tree species as fallow species to management-intensive alley cropping, providing alternatives to shifting cultivation and arresting deforestation and land degradation in the moist tropical forest areas of Asia, Africa and Latin America;
- Carefully planted and managed multispecies systems involving indigenous trees planted around wildlife reserves, acting as a buffer zone between such protected areas and the agricultural lands;
- Healthy cattle grazing on perennial peanut crops under widely spaced, paired-rows of slash pine in rural Florida, with other pines protecting citrus plants against frost damage;
- Extensive stands of black walnut and other timber trees planted with agricultural crops in northern and mid-western USA, providing enhanced, long-term returns for the farmers.

And so on.

Such a scenario is not unrealistic, but there are many hurdles to overcome before it can be realized. We have examined the technical and socio-economic hurdles. There remains a final hurdle — to dispell any lingering perceptions of agroforestry as a 'second-class technology' or an 'imperialistic ploy' designed to keep the developing countries down. To this end, it may be necessary to incorporate a 'high-tech' element into agroforestry, to underline its status as a 'first-class' technology which offers considerable promise for farmers throughout the world's tropical regions.

References

Agamuthu, P. and Broughton, W. J. 1985. Nutrient cycling within the developing oil palm-legume ecosytem. *Agriculture, Ecosystems and Environment* 13: 111-123.

Ahenkorah, Y. 1975. Use of radioactive phosphorus in determining efficiency of fertilizer utilization by cacao plantation. *Plant Soil* 42: 429-439.

Alpizar, L., Fassbender, H. W., Heuveldop, J., Foelster, H. and Enriquez, G. 1986. Modelling agroforestry systems of cacao *(Theobroma cacao)* with laurel *(Cordia alliodora)* and poro *(Erythrina poeppigiana)* in Costa Rica. Part I. Inventory of organic matter and nutrients. *Agroforestry Systems* 4: 175-190.

Alpizar, O. L. A. 1985. Untersuchungen uber den Stoffaushalt einiger agroforstlicher Systeme in Costa Rica. Dokt. Diss., Georg-August Univ., Goettingen, West Germany.

Alvarez-Buylla Roces, M. E., Lazos Chavero, E. and Garcia-Barrios, J. R. 1989. Homegardens of a humid tropical region in south-east Mexico: An example of an agroforestry cropping system in a recently established community. *Agroforestry Systems* 8: 133-156.

Alvim, R. and Nair, P. K. R. 1986. Combination of cacao with other plantation crops: An agroforestry system in south-east Bahia, Brazil. *Agroforestry Systems* 4: 3-15.

Anderson, D. 1987. *The economics of afforestation: A case study in Africa.* Occasional Paper No. 1 (New Series). Johns Hopkins Press, Baltimore, USA.

Andriesse, J. P. and Koopmans, T. T. 1984. A monitoring study of nutrient cycles in soils used for shifting cultivation under various climatic conditions in tropical Asia. I. The influence of simulated burning on form and availability of plant nutrients. *Agriculture, Ecosystems and Environment* 12: 1-6.

Andriesse, J. P., Koopmans, T. T. and Schelhaas, R. M. 1987. A monitoring study of nutrient cycles in soils used for shifting cultivation under various climatic conditions in tropical Asia. III. *Agriculture, Ecosystems and Environment* 19: 285-332.

Andriesse, J. P. and Schelhaas, R. M. 1985. Monitoring project of nutrient cycling in soils used for shifting cultivation under various climatic conditions in Asia. Progress Report 3. Royal Tropical Institute, Amsterdam.

Aranguren, J., Escalante, G. and Herrera, R. 1982. Nitrogen cycle of tropical perennial crops under shade trees. I. Coffee. II. Cacao. *Plant Soil* 67: 247-269.

Arnold, J. E. M. 1984. Economic considerations in agrforestry projects. *Agroforestry Systems* 1: 299-311.

——. 1987. Economic considerations in agroforestry. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Ashraf, M. 1990. Economic evaluation of alley cropping for sustainable agriculture in humid West Africa. Univ. Florida, USA (paper submitted for publication).

Atkinson, D. 1974. Some observations on the distribution of root activity in apple trees. *Plant Soil* 40: 333-342.

Atkinson, D., Bhatt, K. K. S., Mason, P. A., Coutts, M. P. and Read, D. J. (eds.) 1983. *Tree root systems and their mycorrhizas.* Martinus Nijhoff, The Hague, The Netherlands.

Atta-Krah, A. N. 1989. *Alley Farming Research Network for Africa Newsletter* 1. IITA, Ibadan, Nigeria.

Atta-Krah, A. N. and Sumberg, J. E. 1988. Studies with *Gliricidia sepium* for crop/livestock production systems in West Africa. *Agroforestry Systems* 6: 97-118.

Atta-Krah, A. N., Sumberg, J. E. and Reynolds, L. 1985. *Leguminous fodder trees in the farming systems: An overview of research at the humid zone programme of ILCA in south-western Nigeria.* ILCA, Ibadan, Nigeria.

Avery, M. E., Cannell, M. G. R. and Ong, C. K. (eds.) 1990. *Biophysical research for Asian agroforestry.* Oxford Press, New Delhi, India.

Bannister, M. E. and Nair, P. K. R. 1990. Alley cropping as a sustainable agricultural technology for the hillsides of Haiti: Experience of an agroforestry outreach project. *American Journal of Alternative Agriculture* (in press).

Balasubramanian, V. and Sekayange, L. 1990. Area harvests equivalency ratios for measuring efficiency in multiseason intercropping. *Agronomy Journal* 82: 519-522.

Bavappa, K. V. A., Nair, M. K. and Kumar, T. P. (eds.) 1982. *The arecanut palm (*Areca catechu *Linn.).* Central Plantation Crops Research Institute, Kasaragod, India.

Becker, B. 1983. The contribution of wild plants to human nutrition in the Ferlo (Northern Senegal). *Agroforestry Systems* 1: 257-267.

——. 1984. Wildpflanzen in der Ernaehrung der Bevolkerung afrikanischer Trockengebiete: Drei Fallstudien aus Kenia und Senegal. Goettinger Beitrage zur land- und Forstwirtschaft in den Tropen und Subtropen, 5. Univ. Goettingen, West Germany.

Beer, J. 1987. Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. *Agroforestry Systems* 5: 3-13.

Beer, J. 1989. Litter production and nutrient cycling in coffee *(Coffea arabica)* or cacao *(Theobroma cacao)* plantation with shade trees. *Agroforestry Systems* 7: 103-114.

Bene, J. G., Beall, H. W. and Cote, A. 1977. *Trees, food and people: Land management in the tropics. IDRC, Ottawa, Canada.*

Betters, D. R. 1988. Planning optimal economic strategies for agroforestry systems. *Agroforestry Systems* 7: 17-31.

BIFAD. *Sustainable Agriculture Information Exchange Newsletter* 1 (1) January 1990. Washington, USA.

Bognettean-Verlinden, E. 1980. *Study of impact of windbreak in Majjia valley, Niger.* Agricultural Univ., Wageningen, The Netherlands.

Bond, G. 1976. The results of the IBP survey of root-nodule formation in non-leguminous angiosperms. In Nutman, P. S. (ed.) *Symbiotic nitrogen fixation by plants.* Cambridge Univ. Press, London, UK.

Bowen, G. D. 1985. Roots as a component of tree productivity. In Cannell, M. G. R. and Jackson, J. E. (eds.) *Attributes of trees as crop plants.* Institute of Terrestrial Ecology, Huntingdon, UK.

Brewbaker, J. L. 1987a. Significant nitrogen-fixing trees in agroforestry systems. In Gholz, H. L. (ed.) *Agroforestry: Realities, possibilities and potentials.* Martinus Nijhoff, Dordrecht, The Netherlands.

——. 1987b. Leucaena: A multipurpose tree genus for tropical agroforestry. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Brewbaker, J. L., Van Den Beldt, R. R. and MacDicken, K. G. 1982. Nitrogen-fixing tree resources: Potentials and limitations. In Graham, P. H. and Harris, S. C. (eds.) *BNF technology for tropical agriculture.* CIAT, Cali, Colombia.

Budelman, A. 1988. The decomposition of the leaf mulches of *Leucaena leucocephala, Gliricidia sepium* and *Flemingia macrophylla* under humid tropical conditions. *Agroforestry Systems* 7: 33-45, 47-62.

——. 1989. Nutrient composition of the leaf biomass of three selected woody leguminous species. *Agroforestry Systems* 8: 39-51.

Budowski, G. 1987. The development of agroforestry in Central America. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

CARE. 1986. Uganda village forestry project. CARE, New York, USA (unpublished).

Chowdhry, K. 1985. Social forestry: Who benefits? In *Community forestry: Socio-economic aspects.* FAO/East-West Center, Bangkok, Thailand.

Coleman, D. C. 1976. A review of root production processes and their influence on the soil biota in terrestrial ecosystems. In Anderson, J. M. and MacFayden, A. (eds.) *The role of terrestrial and acquatic organisms in decomposition processes.* Blackwell, Oxford, UK.

Commerford, N. B., Kidder, G. and Mollitor, A. V. 1984. Importance of subsoil fertility to forest plant nutrition. In Stone, E. L. (ed.) *Forest soils and treatment impacts: Proceedings of the Sixth North American Forest Soils Conference.* Univ. Tennessee, Knoxville, USA.

Connor, D. J. 1983. Plant stress factors and their influence on production of agroforestry plant associations. In Huxley, P. A. (ed.) *Plant research and agroforestry.* ICRAF, Nairobi, Kenya.

Cook, C. C. and Grut, M. 1989. *Agroforestry in sub-Saharan Africa: A farmer's perspective.* World Bank, Washington DC, USA.

Corlett, J. E., Ong, C. K. and Black, C. R. 1989. Modification of microclimate in intercropping and alley-cropping systems. In Reifsnyder, W. S. and Darnhofer, T. O. (eds.) *Meteorology and agroforestry.* ICRAF/ WMO/UNEP/GTZ, Nairobi, Kenya.

Coulson, C. L., Mungai, D. N., Stigter, C. J., Mwangi, P. W. and Njiru, D. M. 1989. Studies of sustainable crop yield improvement through an agroforestry intervention. Univ. Nairobi/Kenya Forest Research Institute/Kenya Agricultural Research Institute, Nairobi, Kenya (unpublished).

Dommergues, Y. R. 1987. The role of biological nitrogen fixation in agroforestry. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Duguma, B., Kang, B. T. and Okali, D. U. U. 1988. Effect of pruning intensities of three woody leguminous species grown in alley cropping with maize and cowpea on an alfisol. *Agroforestry Systems* 6: 19-35.

Duncan, P. 1960. *Sotho laws and customs.* Oxford Univ. Press, Oxford, UK.

Edwards, C. A., Lal, R., Madden, P., Miller, R. H. and House, G. (eds.) 1990. *Sustainable agricultural systems.* Soil and Water Conservation Society, Ankeny, Iowa, USA.

Eisenberg, J. F. and Harris, L. D. 1987. Agriculture forestry and wildlife resources: Perspectives from the Western hemisphere. In Gholz, H. L. (ed.) *Agroforestry: Realities, possibilities and potentials.* Martinus Nijhoff, The Hague, The Netherlands.

Ehui, S. K., Kang, B. T. and Spencer, D. S. C. 1990. Economic analysis of soil erosion effects in alley cropping, no-till and bush fallow systems in south-western Nigeria. *Agricultural Systems* (in press).

Energy/Development Intetrnational. 1986. Economics and organizational aspects of private tree farming to increase fuelwood production in developing countries. Report to USAID (LAC-5728-G-SS-4075-00) Washington DC, USA (unpublished).

Etherington, D. M. and Mathews, P. J. 1983. Approaches to the economic evaluation of agroforestry farming systems. *Agroforestry Systems* 1: 347-366.

Evans, D. O. and Rotar, P. P. 1987. *Sesbania in agriculture.* Westview Tropical Agriculture Series No. 8. Westview Press, Boulder, USA and London, UK.

Ewel, J., Benedict, F., Berish, C., Brown, B., Gliessman, S., Amador, M., Bermudez, R., Martinez, A., Miranda, R. and Price, N. 1982. Leaf area, light transmission, roots and leaf damage in nine tropical plant communities. *Agroecosystems* 7: 305-326.

Ewel, J. 1986. Designing agricultural ecosystems for the humid tropics. *Annual Review of Ecological Systems* 17: 245-271.

FAO. 1982. *Tropical forest resources.* FAO, Rome, Italy.

—. 1983. *Food and fruit-bearing forest species. 1. Examples from Africa.* FAO, Rome, Italy.

—. 1985. *Tree growing by rural people.* FAO Forestry Paper 64. FAO, Rome, Italy.

—. 1987. *Small-scale forestry-based processing enterprises.* FAO, Rome, Italy.

Fassbender, H. W., Alpizar, L., Heuveldop, J., Foelster, H. and Enriquez, G. 1988. Modelling agroforestry systems of cacao *(Theobroma cacao)* with laurel *(Cordia alliodora)* and poro *(Erythrina poeppigiana)* in Costa Rica. III. Cycles of organic matter and nutrients. *Agroforestry Systems* 6: 49-62.

Felker, P. 1978. State-of-the-art: *Acacia albida* as a complementary intercrop with annual crops. Report to USAID. Univ. California, Riverside, USA.

—. (ed.). 1986. Establishment and productivity of tree planting in semi-arid regions. *Forest Ecology and Management* 16 V-VIII (Special Issue).

Fernandes, E. C. M. and Nair, P. K. R. 1986. An evaluation of the structure and function of tropical homegardens. *Agricultural Systems* 21: 279-310.

Filius, A. M. 1982. Economic aspects of agroforestry. *Agroforestry Systems* 1: 29-39.

Foelster, H., De las Salas, G. and Khanna, P. 1976. A tropical evergreen forest site with perched water table, Magdalena valley, Colombia: Biomass and bioelement inventory of primary and secondary vegetation. *Oecologia Plantarum* 11: 297-320.

Fogel, R. 1985. Roots as primary producers in below-ground ecosystems. In Fitter, A. H. (ed.) *Ecological interactions in soil.* Blackwell, Oxford, UK.

Fortmann, L. 1985. Tree tenure: An analytical framework for agroforestry projects. In Raintree, J. B. (ed.) *Land, trees and tenure.* Land Tenure Center, Univ. Wisconsin, USA/ICRAF, Nairobi, Kenya.

—. 1988. Tree tenure factor in agroforestry with particular reference to Africa. In Fortmann, L. and Bruce, J. W. (eds.) *Whose trees? Proprietary dimensions of forestry.* Westview Press, Boulder, USA.

Fortmann, L. and Riddell, J. 1985. *Trees and tenure: An annotated bibliography for agroforesters and others.* Land Tenure Center, Univ. Wisconsin, USA/ICRAF, Nairobi, Kenya.

Francis, P. A. 1989. Land tenure systems and the adoption of alley farming. In Kang, B. T. and Reynolds, L. (eds.) *Alley farming in the humid and subhumid tropics.* IDRC, Ottawa, Canada.

Francis, P. A. and Atta-Krah, A. N. 1989. Sociological and ecological factors in technology adoption: Fodder trees in south-eastern Nigeria. *Expt'l Agri.* 25: 1-10.

Gauthier, D. L., Diem, H. G., Dommergues, Y. R. and Ganry, F. 1985. Assessment of N_2 fixation by *Casuarina equisetifolia* inoculated with *Frankia* ORS 021001 using ^{15}N methods. *Soil Biology and Biochemistry* 17: 375-379.

Ghosh, S. P., Kumar, B. M., Kabeerathumma, S. and Nair, G. M. 1989. Productivity, soil fertility and soil erosion under cassave-based agroforestry systems. *Agroforestry Systems* 8: 67-82.

Gibson, A. H., Dreyfus, B. L. and Dommergues, Y. R. 1982. Nitrogen fixation by legumes. In Dommergues, Y. R. and Diem, H. G. (eds.) *Microbiology of tropical soil and plant productivity.* Martinus Nijhoff, The Hague, The Netherlands.

Gill, H. S. and Abrol, I. P. 1986. Salt-affected soils and their amelioration through afforestation. In Prinsley, R. T. and Swift, M. J. (eds.) *Amelioration of soil by trees: A review of current concepts and practices.* Commonwealth Science Council, London, UK.

Glover, N. and Beer, J. 1986. Nutrient cycling in two traditional Central American agroforestry systems. *Agroforestry Systems* 4: 77-87.

Golley, F. B. 1986. Chemical plant-soil relationships in tropical forests. *Journal of Trop. Ecol.* 2: 219-229.

Gregersen, H. M. and Contreras, A. 1979. *Economic analysis of forestry projects.* Forestry Paper No. 17. FAO, Rome, Italy.

Gregersen, H., Draper, S., and Elz, D. (eds.) 1988. *People and trees: The role of social forestry in sustainable development.* Economic Development Institute, World Bank, Washington DC, USA.

Grewal, S. S. and Abrol, I. P. 1986. Agroforestry on alkali soils: Effect of some management practices on initial growth, biomass accumulation and chemical composition of selected tree species. *Agroforestry Systems* 4: 221-232.

Gupta, T. 1982. The economics of tree crops on marginal agricultural lands with special reference to the hot arid region in Rajasthan, India. *International Tree Crops Journal* 2: 155-192.

Harrison, P. 1989. *The greening of Africa: Breaking through in the battle for land and food.* Paladin, London, UK.

Harper, J. L. 1977. *Population biology of plants.* Academic Press, London, UK.

Harrison-Murray, R. S. and Lal, R. 1979. High soil temperature and response of maize to mulching in the lowland humid tropics. In Lal, R. and Greenland, D. J. (eds.) *Soil physical properties and crop production in the tropics.* Wiley, Chichester, UK.

Hermann, R. K. 1977. Growth and production of tree roots: A review. In Marshall, J. K. (ed.) *The below-ground ecosystem: A synthesis of plant-associated processes.* Range Science Department Scientific Series 26. Colorado State Univ., Fort Collins, USA.

Heuveldop, J., Fassbender, H. W., Alpizar, L., Enriquez, G. and Foelster, H. 1988. Modelling agroforestry systems of cacao *(Theobroma cacao)* with laurel *(Cordia alliodora)* and poro *(Erythrina poeppigiana)* in Costa Rica. II. Cacao and wood production, litter production and decomposition. *Agroforestry Systems* 6: 37-48.

Hiebsch, C. K. and R. E. McCollum. 1987. Area x Time equivalency ratio: A method for evaluating the productivity of intercrops. *Agronomy Journal* 79: 15-22.

Hoekstra, D. 1985. *The use of economics in diagnosis and design of agroforestry systems.* Working Paper 29. ICRAF, Nairobi, Kenya.

—. 1987. Economics of agroforestry. *Agroforestry Systems* 5: 293-300.

—. 1990. Economics of agroforestry. In MacDicken, K. G. and Vergara, N. T. (eds.) *Agroforestry: Classification and management.* Wiley, New York, USA .

Hogberg, P. and Kvarnstrom, M. 1982. Nitrogen fixation by the woody legume *Leucaena leucocephala* in Tanzania. *Plant Soil* 66: 21-28.

Hosier, R. H. 1987. The economics of agroforestry and incentives to ecodevelopment. Technical Report No. 2. Presented at seminar on Perspectives in Agroforestry, Washington State Univ., USA, October 1987 (unpublished).

Hoskins, M. W. 1987. Agroforestry and the social milieu. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Huxley, P. A. (ed.) 1983. *Plant research and agroforestry.* ICRAF, Nairobi, Kenya.

Huxley, P. A., Patel, R. Z., Kabaara, A. M. and Mitchell, H. W. 1974. Tracer studies with ^{32}P on the distribution of functional roots in Arabica coffee in Kenya. *Ann. Appl. Biology* 77: 159-180.

ILCA. 1986. Mycorrhizae: Can Africa benefit? *Land and Water — FAO AGLS Newsletter* 27: 3-4.

—. 1987. *Annual Report for 1986.* ILCA, Addis Ababa, Ethiopia.

ICRAF. 1987. *Profile of ICRAF in Africa.* ICRAF, Nairobi, Kenya.

—. 1989. *Annual Report for 1988.* ICRAF, Nairobi, Kenya.

—. 1990. *ICRAF: Strategy to the year 2000.* ICRAF, Nairobi, Kenya.

ICRAF/NFTA. 1989. *Perennial Sesbania species in agroforestry systems: Proceedings of the ICRAF/NFTA Workshop.* ICRAF, Nairobi, Kenya.

ICRISAT. 1989. *Annual Report for 1988.* ICRISAT, Hyderabad, India.

Imbach, A. C., Fassbender, H. W., Borel, R., Beer, J. and Bonnemann, A. 1989. Modelling agroforestry systems of cacao *(Theobroma cacao)* with laurel *(Cordia alliodora)* and poro *(Erythrina poeppigiana)* in Costa Rica. IV. Water balances, nutrient inputs and leaching. *Agroforestry Systems* 8: 267-287.

IRRI. 1974. *Annual Report for 1973.* IRRI, Los Banos, The Philippines.

—. 1975. *Annual Report for 1974.* IRRI, Los Banos, The Philippines.

Ismail, T. 1986. Integration of animals in rubber plantations. *Agroforestry Systems* 4: 55-66.

Janzen, D. H. 1983. No park is an island. *Oikos* 41: 402-410.

Jickling, J. 1989. Short-term economic benefits of agroforestry: A survey. Report to USDA Forestry Support Program (RSSA-BST-5519-R-AG-2188). USDA, Washington DC, USA.

Johns, A.D. 1985. Selective logging and wildlife conservation in tropical rainforest: Problems and recommendations. *Biological Conservation* 31: 355-375.

Johnson, D. V. and Nair, P. K. R. 1984. Perennial-crop-based agroforestry systems in north-east Brazil. *Agroforestry Systems* 2: 281-292.

Jordan, C., Caskey, W., Escalante, G., Herrera, R., Montagnini, F., Todd, R. and Uhl, C. 1983. Nitrogen dynamics during conversion of primary Amazonian rain forest to slash and burn agriculture. *Oikos* 40: 131-139.

Jonsson, K., Fitzgerald, L., Maghembe, J. A. and Hogberg, P. 1988. The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. *Agroforestry Systems* 6: 63-69.

Juo, A. S. R. 1989. New farming systems development in the wetter tropics. *Experimental Agriculture* 25: 145-163.

Juo, A. S. R. and Lal, R. 1977. The effect of fallow and continuous cultivation on the chemical and physical properties of an alfisol in western Nigeria. *Plant Soil* 47: 567-584.

Kang, B. T., Wilson, G. F. and Sipkens, L. 1981. Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* LAM) in southern Nigeria. *Plant Soil* 63: 165-179.

Kang, B. T. and Duguma, B. 1985. Nitrogen movement in alley cropping systems. In Kang, B. T. and van den Heide, J. (eds.) *Nitrogen in farming systems in the humid and subhumid tropics*. Institute of Soil Fertility, Haren, The Netherlands.

Kang, B. T., Grimme, H. and Lawson, T. L. 1985. Alley cropping sequentially cropped maize and cowpea with *Leucaena* on a sandy soil in southern Nigeria. *Plant Soil* 85: 267-277.

Kang, B. T., Reynolds, L. and Atta-Krah, A. N. 1989. Alley farming. *Advances in Agronomy* 43: 315-359.

Kang, B. T. and Wilson, G. F. 1987. The development of alley cropping as a promising agroforestry technology. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development*. ICRAF, Nairobi, Kenya.

Kang, B. T., Wilson, G. F. and Lawson, T. L. 1984. *Alley cropping: A stable alternative to shifting cultivation*. IITA, Ibadan, Nigeria.

Kass, D. 1987. Alley cropping of annual food crops with woody legumes in Costa Rica. In Beer, J. W., Fassbender, H. W. and Heuveldop, J. (eds.) *Advances in agroforestry research: Seminar proceedings*. CATIE, Costa Rica.

Kellman, M. 1979. Soil enrichment by neotropical savanna trees. *Journal of Ecology* 67: 565-577.

Koopmans, T. Th. and Andriesse, J. P. 1982. Baseline study: Monitoring project of nutrient cycling in shifting cultivation, Sri Lanka and Malaysia. Progress Report 1. Royal Tropical Institute, Amsterdam.

Lal, R. 1989. Agroforestry systems and soil surface management of a tropical alfisol. Parts I-VI. *Agroforestry Systems* 8(1): 1-6, 7-29; 8(2): 97-111, 113-132; 8(3): 197-215, 217-238, 239-242.

Lal, R. and Greenland, D. J. (eds.) 1979. *Soil physical properties and crop production in the tropics*. Wiley, Chichester, UK.

LaRue, T. A. and Patterson, T. G. 1981. How much nitrogen do legumes fix? *Advances in Agronomy* 34: 15-38.

Liyanage, L. V. K., Jayasundera, H. P. S., Mathews, D. T. and Fernando, D. N. S. 1989. Integration of pasture, fodder and cattle in coconut smallholdings. *CORD* 5(2): 53-59.

Liyanage, M. de S., Jejwani, K. G. and Nair, P. K. R. 1984. Intercropping under coconuts in Sri Lanka. *Agroforestry Systems* 2: 215-228.

Lundgren, B. 1978. Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands. Report on Forest Ecology and Forest Soils 31. Swedish Univ. Agric. Sciences, Uppsala, Sweden.

Lundgren, B. 1987. Institutional aspects of agroforestry development. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development*. ICRAF, Nairobi, Kenya.

Lundgren, B. 1989. The potential of agroforestry. In Kilewe, A. M., Kealey, K. M. and Kebaara, K. K. (eds.) *Agroforestry Development in Kenya: Proceedings of the second national seminar on agroforestry*. ICRAF, Nairobi, Kenya.

Lundgren, B. and Nair, P. K. R. 1985. Agroforestry for soil conservation. In El-Swaify, S. A., Moldenhauer, W. C. and Lo, A. (eds.) *Soil erosion and conservation*. Soil Conservation Society of North America, Ankey, USA.

MacDicken, K. G. and Brewbaker, J. L. 1985. Descriptive summaries of economically important nitrogen-fixing trees. *NFTA Research Report* 2: 46-54.

MacDicken, K. G. and Vergara, N. T. (eds.) 1990. *Agroforestry: Classification and management*. Wiley, New York, USA.

Macleod, H. L. 1987. Conservation of Oku mountain forest, Cameroon. World Wildlife Fund, Washington DC, USA (unpublished).

Magrath, W. 1984. Microeconomics of agroforestry. In Shapiro, K. H. (ed.) *Agroforestry in developing countries*. Center for Research on Economic Development, Univ. Michigan, Ann Arbor, USA.

Mann, H. S. and Saxena, S. K. 1980. Khejri *(Prosopis cineraria)* in the Indian desert: Its role in agroforestry. CAZRI Monograph 11. Central Arid Zone Research Institute, Jodhpur, Rajasthan, India.

Mathur, H. N., Agarwal, M. C., Babu, R. and Joshie, P. 1979. Benefit-cost ratio of fuel-cum-fodder plantation in Doon valley. *Indian Journal of Soil Conservation* 7: 53-58.

Mathur, R. S., Sharma, K. K. and Ansari, M. Y. 1984. Economics of *Eucalyptus* plantations under agroforestry. *Indian Forester* 110(2): 171-201.

May, P. H., Anderson, A. B., Frazao, J. M. F. and Balik, J. M. 1985. Babassu palm in the agroforestry systems in Brazil's mid-north region. *Agroforestry Systems* 3: 275-295.

Mead, R. and Willey, R. W. 1980. The concept of 'Land Equivalent Ratio' and advantages in yields from intercropping. *Experimental Agriculture* 16: 217-228.

Meek, C. K. 1970. *Land and law customs in colonies.* (2nd edn) Frank & Cass, London, UK.

Michon, G., Mary, F. and Bompard, J. 1986. Multistoried agroforestry garden system in West Sumatra, Indonesia. *Agroforestry Systems* 4: 315-338.

Miehe, S. 1986. *Acacia albida* and other multipurpose trees on the Fur farmlands in the Jebel Marra highlands, western Dafur, Sudan. *Agroforestry Systems* 4: 89-119.

Mittal, S. P. and Singh, P. 1989. Intercropping field crops between rows of *Leucaena leucocephala* under rainfed conditions in northern India. *Agroforestry Systems* 8: 165-172.

Mueller-Dombois, D., Vitousek, P. M. and Bridger, K. W. 1984. *Canopy dieback and ecosystem processes in Pacific forests.* Hawaii Botanical Science Paper 44. Univ. Hawaii, Manoa, Hawaii.

Nair, P. K. R. 1979. *Intensive multiple cropping with coconuts in India: Principles, programmes and prospects*. Verlag Paul Parey, Berlin and Hamburg.

——. 1983. Agroforestry with coconuts and other tropical plantation crops. In Huxley, P. A. (ed.) *Plant research and agroforestry.* ICRAF, Nairobi, Kenya.

——. 1984. *Soil productivity aspects of agroforestry.* ICRAF, Nairobi, Kenya.

——. 1985. Classification of agroforestry systems. *Agroforestry Systems* 3: 97-128.

——. 1987. Soil productivity under agroforestry. In Gholz, H. L. (ed.) *Agroforestry: Realities, possibilities and potentials.* Martinus Nijhoff, Dordrecht, The Netherlands.

——. 1988. Use of perennial legumes in Asian farming systems. In *Green manure in rice farming.* IRRI, Los Banos, The Philippines.

——. (ed.) 1989. *Agroforestry systems in the tropics.* Kluwer, Dordrecht, The Netherlands.

——. 1990. State-of-the-art of agroforestry systems. In *Agroforestry: Principles and practice. Proceedings of an International Conference.* Univ. Edinburgh, July 1989 (in press).

Nair, P. K. R., Gholz, H. L. and Duryea, M. L. (eds.) 1990. *Agroforestry education and training: Present and future.* Kluwer, Dordrecht, The Netherlands.

Ndoye, I. and Dreyfus, B. 1988. N_2 fixation by *Sesbania rostrata* and *Sesbania sesban* estimated using ^{15}N and total N difference methods. *Soil Biology and Biochemistry* 20: 209-213.

Nelliat, E. V. and Bhat, K. S. (eds.) 1979. *Multiple cropping in coconut and arecanut gardens.* Technical Bulletin 3. Central Plantation Crops Research Institute, Kasaragod, India.

NFTA 1983-1990. *NFT highlights.* Nitrogen Fixing Tree Association, Waimanalo, Hawaii.

Ngambeki, D. S. 1985. Economic evaluation of alley cropping leucaena with maize-maize and maize-cowpea in southern Nigeria. *Agricultural Systems* 17: 243-258.

Ngambeki, D. S. and Wilson, G. F. 1984. Economic and on-farm evaluation of alley cropping with *Leucaena leucocephala*, 1980-1983. Activity Consolidated Report. IITA, Nigeria.

Nutman, P. S. 1976. IBP field experiments on nitrogen fixation by nodulated legumes. In Nutman, P. S. (ed.) *Symbiotic nitrogen fixation in plants.* Cambridge Univ. Press, London, UK.

Odigie, G. A., Abu, J. E. and Adeola, A. O. 1989. Effect of alley width and pruning height on crop yield in Gambari, south-western Nigeria. In *Agroforestry: Principles and practice. Proceedings of an International Conference.* Univ. Edinburgh, July 1989 (in press).

Odum, H. T. and Pigeon, R. F. (eds.) 1970. *A tropical rainforest* Vol. III. Office of Information Services, US Atomic Energy Commission, Washington DC, USA.

Oldfield, S. 1986. *Buffer zone management in tropical moist forests: Case studies and guidelines.* IUCN Tropical Forest Programme, Cambridge, UK.

OTA. 1988. *Enhancing agriculture in Africa: A role for US development assistance.* OTA, Washington DC, USA.

Ogle, B. M. and Grivetti, L. E. 1985. Legacy of the chameleon. Edible wild plants in the kingdom of Swaziland: A cultural, ecological and nutritional study. *Ecology of Food and Nutrition* Part I 16(3): 193-208; Parts II-IV, 17(1): 1-6.

Okafor, J. C. 1981. Woody plants of nutritional importance in traditional farming systems of the Nigerian humid tropics. PhD thesis. Univ. Ibadan, Nigeria.

Okafor, J. C. and Fernandes, E. C. M. 1986. Compound farms (homegardens): A predominant agroforestry system involving food and fruit trees with crops and small livestock in the humid lowlands of south-eastern Nigeria. *Agroforestry Systems* 5: 153-168.

Okali, D. U. U. and Sumberg, J. E. 1985. Sheep and goats, men and women: Household relations and small ruminant development in south-west Nigeria. *Agricultural Systems* 18: 39-45.

Ong, C. K., Corlett, J. E., Singh, R. P. and Black, C. R. 1989. Above-and below-ground interactions in agroforestry systems. In *Agroforestry: Principles and practice. Proceedings of an International Conference.* Univ. Edinburgh, July 1989 (in press).

Osemebo, G. J. 1987. Smallholder farmers and forestry development: A study of rural land-use in Bendel, Nigeria. *Agricultural Systems* 24: 31-51.

Ovalle, C., Aronson, J., Del Pozo, A. and Avendano, J. 1990. The espinal: Agroforestry systems of the mediterranean-type climate region of Chile. *Agroforestry Systems* 10: 213-239.

O'Sullivan, T. E. 1985. Farming systems and soil management: The Philippines/Australian development assistance program experience. In Craswell, E. T., Remenyi, J. V. and Nallana, L. G. (eds.) *Soil erosion management.* ACIAR Proccedings Series 6. ACIAR, Canberra, Australia.

Palm, C. A. 1988. Mulch quality and nitrogen dynamics in an alley cropping system in the Peruvian Amazon. PhD Thesis. North Carolina State Univ., Raleigh, USA.

Palm, C. A. and Sanchez, P. A. 1988. *The role of nitrogen, lignin and polyphenolics on the release of nitrogen from some tropical legumes.* North Carolina Agricultural Research Service, Raleigh, USA.

Pickering, D.C. (ed.) 1988. *African agricultural research and technological development. Proceedings of a meeting.* Feldafing, F.R. Germany, 1987. The World Bank, Washington DC, USA.

Plucknett, D. L. 1979. *Managing pasture and cattle under coconuts.* Westview Press, Boulder, USA.

Poore, M. E. D. and Fries, C. 1985. *The ecological effects of Eucalyptus.* FAO Forestry Paper 59. FAO, Rome, Italy.

Poschen, P. 1986. An evaluation of the *Acacia albida*-based agroforestry practices in the Hararghe highlands of eastern Ethiopia. *Agroforestry Systems* 4: 129-143.

Prinsley, R. T. (ed.) 1990. *Agroforestry for sustainable production.* Commonwealth Science Council, London, UK.

Purohit, A. G. and Mukherjee, S. K. 1974. Characterizing root activity of guava trees by radiotracer technique. *Indian Journal of Agricultural Sciences* 44: 575-581.

Raintree, J. B. 1986. *An introduction to agroforestry diagnosis and design.* ICRAF, Nairobi, Kenya.

—. 1987. The state-of-the-art of agroforestry diagnosis and design. *Agroforestry Systems* 5: 219-250.

Raintree, J. B. and Hoskins, M. W. 1988. Appropriate R & D support for forestry extension. In *Planning forestry extension programmes: Report of a regional expert consultation.* FAO, Bangkok, Thailand.

Raintree, J. B. and Turray, F. 1980. Linear programming model of an experimental *Leucaena*-rice alley cropping system. *IITA Research Briefs* 1: 5-7.

Raintree, J. B. and Warner, K. 1986. Agroforestry pathways for the intensification of shifting cultivation. *Agroforestry Systems* 4: 39-54.

Rao, M. R., Sharma, M. M. and Ong, C. K. 1990. A study of the potential of hedgerow intercropping in semi-arid India using a two-way systematic design. *Agroforestry Systems* (in press).

Reiche, C. E. 1987. Advances in economic studies of agroforestry plantations in Central America. In Beer, J. W., Fassbender, H. W. and Heuveldop, J. (eds.) *Advances in agroforestry research: Seminar proceedings*. CATIE, Costa Rica.

—. 1988. Socio-economic approach and analysis of agroforestry systems applied on demonstration farms in Central America. Paper presented at the symposium on Fragile Lands in Latin America: Search for Sustainable Uses, XIV Congress of the Latin American Studies Association, March 1988. New Orleans, Lousiana.

Roberts, N. (ed.) 1989. *Agricultural extension in Africa: A World Bank Symposium*. The World Bank, Washington DC, USA.

Rocheleau, D., Weber, F. and Field-Juma, A. 1988. *Agroforestry in dryland Africa*. ICRAF, Nairobi, Kenya.

Roskoski, J. P. 1981. Nodulation and N_2 fixation by *Inga jinicuil*, a woody legume in coffee plantations. I. Measurement of nodule biomass and field C_2H_2 reduction rates. *Plant Soil* 59: 201-206.

—. 1986. Nitrogen fixation in leguminous trees. *Ceiba* 27: 227-229.

Roskoski, J. P. and van Kessel, C. 1985. Annual, seasonal and diel variation in nitrogen fixing activity in *Inga jinicuil*, a tropical leguminous tree. *Oikos* 44: 306-312.

Russo, R. O. and Budowski, G. 1986. Effect of pollarding frequency on biomass of *Erythrina poeppigiana* as a coffee shade tree. *Agroforestry Systems* 4: 145-162.

Ruthenberg, H. 1980. *Farming systems in the tropics*. (2nd edn) Oxford Univ. Press, London, UK.

Sanchez, P. A. 1987. Soil productivity and sustainability in agroforestry systems. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development*. ICRAF, Nairobi, Kenya.

Sanchez, P. A., Palm, C. A., Davey, C. B., Szott, L. T. and Russell, C. E. 1985. Tree crops as soil improvers in the humid tropics? In Cannell, M. G. R. and Jackson, J. E. (eds.) *Attributes of trees as crop plants*. Institute of Terrestrial Ecology, Huntingdon, UK.

Sanginga, N., Mulongoy, K. and Ayanaba, A. 1986. Inoculation of *Leucaena leucocephala* (Lam.) de Wit with *Rhizobium* and its nitrogen contribution to a subsequent maize crop. *Biological Agriculture and Horticulture* 3: 347-352.

—. 1989. Nitrogen fixation of field-inoculated *Leucaena leucocephala* (Lam.) de Wit estimated by the ^{15}N and difference methods. *Plant Soil* 117: 269-274.

Sauerbeck, D. R. and Johnen, B. G. 1977. Root formation and decomposition during plant growth. In *Soil organic matter studies*. IAEA, Vienna, Austria.

Sauerbeck, D. R., Nonnen, S. and Allard, J. L. 1982. Consumption and turnover of photosynthates in the rhizosphere depending on plant species and growth conditions (abstract). *Transactions of the Twelfth International Congress of Soil Science* 6: 59.

Shankarnarayan, K. A., Harsh, L. N. and Kathju, S. 1987. Agroforestry systems in the arid zones of India. *Agroforestry Systems* 5: 69-88.

Shekhawat, J. S., Sen, S. L. and Somani, L. L. 1988. Evaluation of agroforestry systems under semi-arid conditions of Rajasthan. *Indian Forester* 114 (2): 98-101.

Singh, G., Abrol, I. P. and Cheema, S. S. 1988. Agroforestry on alkali soil: Effect of planting methods and amendments on initial growth, biomass accumulation and chemical composition of mesquite *(Prosopis juliflora)* with inter-space planted with and without Karnal grass (*Diplachne fusca* Linn. P. Beauv.). *Agroforestry Systems* 7: 135-160.

Smith, M. A. 1983. Evaluation of tropical grasses in increasing shade under coconut canopies. *Experimental Agriculture* 19: 153-161.

Smith, M. A. and Whiteman, P. C. 1983. Rotational grazing experiments under coconuts at Lingatu Estate, Russell Islands. Technical Report. Department of Agriculture, Univ. of Queensland, Australia.

Soemarwoto, O. 1987. Homegardens: A traditional agroforestry system with a promising future. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Spears, J. 1987. Agroforestry: A development bank perspective. In Steppler, H. A. and Nair, P. K. R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Steel, R. J. H. and Whiteman, P. C. 1980. Pasture species evaluation: Pasture, fertilizer requirements and weed control in the Solomon Islands. Technical Report, Department of Agriculture, Univ. of Queensland, Australia.

Steppler, H. A. and Nair, P. K. R. (eds.) 1987. *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Sumberg, J. E., MacIntire, J., Okali, C. and Atta-Krah, A. N. 1987. Economic analysis of alley farming with small ruminants. *ILCA Bulletin* 28: 2-6.

Szott, L. T. 1987. Improving the productivity of shifting cultivation in the Amazon basin of Peru through the use of leguminous vegetation. PhD thesis. North Carolina State Univ., Raleigh, USA.

Szott, L. T., Fernandes, E. C. M. and Sanchez, P. A. 1989. Soil-plant interactions in agroforestry systems. In *Agroforestry: Principles and practice. Proceedings of an International Conference.* Univ. Edinburgh, July 1989 (in press).

Thomas, G. W. 1989. Sustainable agriculture: Timely thrust for international development. Paper presented to the Division of Agriculture, National Association of State Universities and Land-Grant Colleges, November 1989, Washington DC, USA.

Toky, O. P. and Ramakrishnan, P. S. 1983. Secondary succession following slash and burn agriculture (jhum) in north-eastern India. *Journal of Ecology* 71: 735-757.

Torres, F. 1983. Potential contribution of leucaena hedgerows intercropped with maize to the production of organic nitrogen and fuelwood in the lowland tropics. *Agroforestry Systems* 1: 323-345.

——. 1987. The ICRAF approach to international cooperation. *Agroforestry Systems* 5: 395-417.

TropSoils 1988. *Annual Report of the TropSoils Project for 1987.* Soil Science Department, North Carolina State Univ., Raleigh, USA.

UNESCO. 1984. Action plan for biosphere reserves. *Nature and Resources* 20 (4).

USAID. 1987. Windbreak and shelterbelt technology for increasing agricultural production. S&T/FNR, USAID, Washington DC, USA.

van Kessel, C. and Roskoski, J. P. 1981. Nodulation and N_2 fixation by *Inga jinicuil,* a woody legume in coffee plantations. II. Effect of soil nutrients on nodulation and N_2 fixation. *Plant Soil* 59: 207-216.

van Orsdol, K. G. 1987. Buffer-zone agroforestry in tropical forest regions. Report to USDA Forestry Support Program/USAID (RSSA-BST-5519-R-AG-2188) USDA/FSP, Washington DC, USA.

Vandermeer, J. 1989. *The ecology of intercropping.* Cambridge Univ. Press, Cambridge, UK.

Verinumbe, I., Knipsheer, H. and Enabor, E. E. 1984. The economic potential of leguminous tree crops in zero-tillage cropping in Nigeria: A linear programming model. *Agroforestry Systems* 2: 129-138.

von Carlowitz, P. G. 1986. *Multipurpose tree and shrub seed directory.* ICRAF, Nairobi, Kenya.

——. 1987. ICRAF's multipurpose tree and shrub information system. *Agroforestry Systems* 5: 319-338.

von Maydell, H.-J. 1986. *Trees and shrubs of the Sahel: Their characteristics and uses.* GTZ, Eschborn, Germany.

——. 1987. Agroforestry in the dry zones of Africa: Past, present and future. In Steppler, H.A. and Nair, P.K.R. (eds.) *Agroforestry: A decade of development.* ICRAF, Nairobi, Kenya.

Walker, T. S. 1987. Economic prospects for agroforestry intervention in Indian SAT: Implication for research resource allocation at ICRISAT. Economic Group Progress Report 79. ICRISAT, Hyderabad, India.

Warkentin, M. E., Nair, P. K. R., Ruth, S. R. and Sprague, K. 1990. A knowledge-based expert system for planning and design of agroforestry systems. *Agroforestry Systems* 11: 71-83.

Warui, C. M. 1980. Research on agroforestry at the coast, Kenya. In Buck, L. (ed.) *Proceedings of the Kenya national seminar on agroforestry*. ICRAF, Nairobi, Kenya.

Watson, G. A. 1983. Development of mixed tree and food crop systems in the humid tropics: A response to population pressure and deforestation. *Experimental Agriculture* 19: 311-332.

Watson, H. R. and Laquihon, A. 1985. *Sloping Agricultural Land Technology (SALT) as developed by the Mindanao Baptist Rural Life Center. Proceedings of workshop on Protection and amelioration roles of agroforestry*. Institute of Forest Conservation, UPLB, Los Banos, The Philippines.

Wiersum, K. F. 1986. Ecological aspects of agroforestry with special emphasis on tree-soil interactions: Lecture notes. FONC Project Communication 1986-16. Fakultas Kerhuanan Universiti Gadjah Mada, Jogjakarta, Indonesia.

Willey, R. W. 1985. Evaluation and presentation of intercropping advantages. *Experimental Agriculture* 21: 119-133.

Withington, D., Glover, N. and Brewbaker, J. L. (eds.) 1987. *Gliricidia sepium (Jacq.) Walp.: Management and improvement*. Nitrogen Fixing Tree Association Publication 87-01. NFTA, Waimanalo, Hawaii.

World Bank. 1978. *Forestry sector review*. World Bank, Washington DC, USA.

Yamoah, C. F., Agboola, A. A. and Mulongoy, K. 1986a. Decomposition, nitrogen release and weed control by prunings of selected alley cropping shrubs. *Agroforestry Systems* 4: 247-254.

Yamoah, C. F., Agboola, A. A. and Wilson, G. F. 1986b. Nutrient competition and maize performance in alley cropping systems. *Agroforestry Systems* 4: 247-254.

Young, A. 1988. Agroforestry and its potential to contribute to land development in the tropics. *Journal of Biogeography*. 15: 19-30.

—. 1989. *Agroforestry for soil conservation*. CAB International, Wallingford, Oxford, UK/ICRAF, Nairobi, Kenya.

Distributors of World Bank Publications

ARGENTINA
Carlos Hirsch, SRL
Galeria Guemes
Florida 165, 4th Floor-Ofc. 453/465
1333 Buenos Aires

AUSTRALIA, PAPUA NEW GUINEA, FIJI, SOLOMON ISLANDS, VANUATU, AND WESTERN SAMOA
D.A. Books & Journals
648 Whitehorse Road
Mitcham 3132
Victoria

AUSTRIA
Gerold and Co.
Graben 31
A-1011 Wien

BAHRAIN
Bahrain Research and Consultancy Associates Ltd.
P.O. Box 22103
Manama Town 317

BANGLADESH
Micro Industries Development Assistance Society (MIDAS)
House 5, Road 16
Dhanmondi R/Area
Dhaka 1209

Branch offices:
156, Nur Ahmed Sarak
Chittagong 4000

76, K.D.A. Avenue
Kulna

BELGIUM
Jean De Lannoy
Av. du Roi 202
1060 Brussels

BRAZIL
Publicacoes Tecnicas Internacionais Ltda.
Rua Peixoto Gomide, 209
01409 Sao Paulo, SP

CANADA
Le Diffuseur
C.P. 85, 1501B rue Ampère
Boucherville, Québec
J4B 5E6

CHINA
China Financial & Economic Publishing House
8, Da Fo Si Dong Jie
Beijing

COLOMBIA
Infoenlace Ltda.
Apartado Aereo 34270
Bogota D.E.

COTE D'IVOIRE
Centre d'Edition et de Diffusion Africaines (CEDA)
04 B.P. 541
Abidjan 04 Plateau

CYPRUS
MEMRB Information Services
P.O. Box 2098
Nicosia

DENMARK
SamfundsLitteratur
Rosenoerns Allé 11
DK-1970 Frederiksberg C

DOMINICAN REPUBLIC
Editora Taller, C. por A.
Restauración e Isabel la Católica 309
Apartado Postal 2190
Santo Domingo

EL SALVADOR
Fusades
Avenida Manuel Enrique Araujo #3530
Edificio SISA, 1er. Piso
San Salvador

EGYPT, ARAB REPUBLIC OF
Al Ahram
Al Galaa Street
Cairo

The Middle East Observer
8 Chawarbi Street
Cairo

FINLAND
Akateeminen Kirjakauppa
P.O. Box 128
SF-00101
Helsinki 10

FRANCE
World Bank Publications
66, avenue d'Iéna
75116 Paris

GERMANY, FEDERAL REPUBLIC OF
UNO-Verlag
Poppelsdorfer Allee 55
D-5300 Bonn 1

GREECE
KEME
24, Ippodamou Street Platia Plastiras
Athens-11635

GUATEMALA
Librerias Piedra Santa
5a. Calle 7-55
Zona 1
Guatemala City

HONG KONG, MACAO
Asia 2000 Ltd.
6 Fl., 146 Prince Edward Road, W.
Kowloon
Hong Kong

HUNGARY
Kultura
P.O. Box 149
1389 Budapest 62

INDIA
Allied Publishers Private Ltd.
751 Mount Road
Madras - 600 002

Branch offices:
15 J.N. Heredia Marg
Ballard Estate
Bombay - 400 038

13/14 Asaf Ali Road
New Delhi - 110 002

17 Chittaranjan Avenue
Calcutta - 700 072

Jayadeva Hostel Building
5th Main Road Gandhinagar
Bangalore - 560 009

3-5-1129 Kachiguda Cross Road
Hyderabad - 500 027

Prarthana Flats, 2nd Floor
Near Thakore Baug, Navrangpura
Ahmedabad - 380 009

Patiala House
16-A Ashok Marg
Lucknow - 226 001

INDONESIA
Pt. Indira Limited
Jl. Sam Ratulangi 37
P.O. Box 181
Jakarta Pusat

ITALY
Licosa Commissionaria Sansoni SPA
Via Benedetto Fortini, 120/10
Casella Postale 552
50125 Florence

JAPAN
Eastern Book Service
37-3, Hongo 3-Chome, Bunkyo-ku 113
Tokyo

KENYA
Africa Book Service (E.A.) Ltd.
P.O. Box 45245
Nairobi

KOREA, REPUBLIC OF
Pan Korea Book Corporation
P.O. Box 101, Kwangwhamun
Seoul

KUWAIT
MEMRB Information Services
P.O. Box 5465

MALAYSIA
University of Malaya Cooperative Bookshop, Limited
P.O. Box 1127, Jalan Pantai Baru
Kuala Lumpur

MEXICO
INFOTEC
Apartado Postal 22-860
14060 Tlalpan, Mexico D.F.

MOROCCO
Société d'Etudes Marketing Marocaine
12 rue Mozart, Bd. d'Anfa
Casablanca

NETHERLANDS
InOr-Publikaties b.v.
P.O. Box 14
7240 BA Lochem

NEW ZEALAND
Hills Library and Information Service
Private Bag
New Market
Auckland

NIGERIA
University Press Limited
Three Crowns Building Jericho
Private Mail Bag 5095
Ibadan

NORWAY
Narvesen Information Center
Book Department
P.O. Box 6125 Etterstad
N-0602 Oslo 6

OMAN
MEMRB Information Services
P.O. Box 1613, Seeb Airport
Muscat

PAKISTAN
Mirza Book Agency
65, Shahrah-e-Quaid-e-Azam
P.O. Box No. 729
Lahore 3

PERU
Editorial Desarrollo SA
Apartado 3824
Lima

PHILIPPINES
National Book Store
701 Rizal Avenue
P.O. Box 1934
Metro Manila

International Book Center
Fifth Floor, Filipinas Life Building
Ayala Avenue, Makati
Metro Manila

POLAND
ORPAN
Palac Kultury i Nauki
00-901 Warszawa

PORTUGAL
Livraria Portugal
Rua Do Carmo 70-74
1200 Lisbon

SAUDI ARABIA, QATAR
Jarir Book Store
P.O. Box 3196
Riyadh 11471

MEMRB Information Services
Branch offices:
Al Alsa Street
Al Dahna Center
First Floor
P.O. Box 7188
Riyadh

Haji Abdullah Alireza Building
King Khaled Street
P.O. Box 3969
Damman

33, Mohammed Hassan Awad Street
P.O. Box 5978
Jeddah

SINGAPORE, TAIWAN, MYANMAR, BRUNEI
Information Publications Private, Ltd.
02-06 1st Fl., Pei-Fu Industrial Bldg.
24 New Industrial Road
Singapore 1953

SOUTH AFRICA, BOTSWANA
For single titles:
Oxford University Press Southern Africa
P.O. Box 1141
Cape Town 8000

For subscription orders:
International Subscription Service
P.O. Box 41095
Craighall
Johannesburg 2024

SPAIN
Mundi-Prensa Libros, S.A.
Castello 37
28001 Madrid

Librería Internacional AEDOS
Consell de Cent, 391
08009 Barcelona

SRI LANKA AND THE MALDIVES
Lake House Bookshop
P.O. Box 244
100, Sir Chittampalam A. Gardiner Mawatha
Colombo 2

SWEDEN
For single titles:
Fritzes Fackboksforetaget
Regeringsgatan 12, Box 16356
S-103 27 Stockholm

For subscription orders:
Wennergren-Williams AB
Box 30004
S-104 25 Stockholm

SWITZERLAND
For single titles:
Librairie Payot
6, rue Grenus
Case postale 381
CH 1211 Geneva 11

For subscription orders:
Librairie Payot
Service des Abonnements
Case postale 3312
CH 1002 Lausanne

TANZANIA
Oxford University Press
P.O. Box 5299
Dar es Salaam

THAILAND
Central Department Store
306 Silom Road
Bangkok

TRINIDAD & TOBAGO, ANTIGUA BARBUDA, BARBADOS, DOMINICA, GRENADA, GUYANA, JAMAICA, MONTSERRAT, ST. KITTS & NEVIS, ST. LUCIA, ST. VINCENT & GRENADINES
Systematics Studies Unit
#9 Watts Street
Curepe
Trinidad, West Indies

TURKEY
Haset Kitapevi, A.S.
Istiklal Caddesi No. 469
Beyoglu
Istanbul

UGANDA
Uganda Bookshop
P.O. Box 7145
Kampala

UNITED ARAB EMIRATES
MEMRB Gulf Co.
P.O. Box 6097
Sharjah

UNITED KINGDOM
Microinfo Ltd.
P.O. Box 3
Alton, Hampshire GU34 2PG
England

URUGUAY
Instituto Nacional del Libro
San Jose 1116
Montevideo

VENEZUELA
Libreria del Este
Aptdo. 60.337
Caracas 1060-A

YUGOSLAVIA
Jugoslovenska Knjiga
P.O. Box 36
Trg Republike
YU-11000 Belgrade

RECENT WORLD BANK TECHNICAL PAPERS *(continued)*

No. 99 International Commission on Irrigation and Drainage, *Planning the Management, Operation, and Maintenance of Irrigation and Drainage Systems: A Guide for the Preparation of Strategies and Manuals* (also in French, 99F)

No. 100 Veldkamp, *Recommended Practices for Testing Water-Pumping Windmills*

No. 101 van Meel and Smulders, *Wind Pumping: A Handbook*

No. 102 Berg and Brems, *A Case for Promoting Breastfeeding in Projects to Limit Fertility*

No. 103 Banerjee, *Shrubs in Tropical Forest Ecosystems: Examples from India*

No. 104 Schware, *The World Software Industry and Software Engineering: Opportunities and Constraints for Newly Industrialized Economies*

No. 105 Pasha and McGarry, *Rural Water Supply and Sanitation in Pakistan: Lessons from Experience*

No. 106 Pinto and Besant-Jones, *Demand and Netback Values for Gas in Electricity*

No. 107 Electric Power Research Institute and EMENA, *The Current State of Atmospheric Fluidized-Bed Combustion Technology*

No. 108 Falloux, *Land Information and Remote Sensing for Renewable Resource Management in Sub-Saharan Africa: A Demand-Driven Approach* (also in French, 108F)

No. 109 Carr, *Technology for Small-Scale Farmers in Sub-Saharan Africa: Experience with Food Crop Production in Five Major Ecological Zones*

No. 110 Dixon, Talbot, and Le Moigne, *Dams and the Environment: Considerations in World Bank Projects*

No. 111 Jeffcoate and Pond, *Large Water Meters: Guidelines for Selection, Testing, and Maintenance*

No. 112 Cook and Grut, *Agroforestry in Sub-Saharan Africa: A Farmer's Perspective*

No. 113 Vergara and Babelon, *The Petrochemical Industry in Developing Asia: A Review of the Current Situation and Prospects for Development in the 1990s*

No. 114 McGuire and Popkins, *Helping Women Improve Nutrition in the Developing World: Beating the Zero Sum Game*

No. 115 Le Moigne, Plusquellec, and Barghouti, *Dam Safety and the Environment*

No. 116 Nelson, *Dryland Management: The "Desertification" Problem*

No. 117 Barghouti, Timmer, and Siegel, *Rural Diversification: Lessons from East Asia*

No. 118 Pritchard, *Lending by the World Bank for Agricultural Research: A Review of the Years 1981 through 1987*

No. 119 Asia Region Technical Department, *Flood Control in Bangladesh: A Plan for Action*

No. 120 Plusquellec, *The Gezira Irrigation Scheme in Sudan: Objectives, Design, and Performance*

No. 121 Listorti, *Environmental Health Components for Water Supply, Sanitation, and Urban Projects*

No. 122 Dessing, *Support for Microenterprises: Lessons for Sub-Saharan Africa*

No. 123 Barghouti and Le Moigne, *Irrigation in Sub-Saharan Africa: The Development of Public and Private Systems*

No. 124 Zymelman, *Science, Education, and Development in Sub-Saharan Africa*

No. 125 van de Walle and Foster, *Fertility Decline in Africa: Assessment and Prospects*

No. 126 Davis, MacKnight, IMO Staff, and Others, *Environmental Considerations for Port and Harbor Developments*

No. 127 Doolette and Magrath, editors, *Watershed Development in Asia: Strategies and Technologies*

No. 128 Gastellu-Etchegorry, editor, *Satellite Remote Sensing for Agricultural Projects*

No. 129 Berkoff, *Irrigation Management on the Indo-Gangetic Plain*

No. 130 Agnes Kiss, editor, *Living with Wildlife: Wildlife Resource Management with Local Participation in Africa*

The World Bank

Headquarters
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

Telephone: (202) 477-1234
Facsimile: (202) 477-6391
Telex: WUI 64145 WORLDBANK
RCA 248423 WORLDBK
Cable Address: INTBAFRAD
WASHINGTONDC

European Office
66, avenue d'Iéna
75116 Paris, France

Telephone: (1) 40.69.30.00
Facsimile: (1) 47.20.19.66
Telex: 842-620628

Tokyo Office
Kokusai Building
1-1 Marunouchi 3-chome
Chiyoda-ku, Tokyo 100, Japan

Telephone: (3) 214-5001
Facsimile: (3) 214-3657
Telex: 781-26838

Cover design by Walton Rosenquist

ISBN 0-8213-1702-4