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AGROFORESTRY FOR SOIL CONSERVATION

ANTHONY YOUNG

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International Council for Research in Agroforestry

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CONTENTS

FOREWORD

It is with particular pleasure and satisfaction that I write this foreword—not only, or even mainly, the satisfaction of a Director General who sees the publication of a major piece of work from his organization. Much more, it is the pleasure and satisfaction, even excitement, of one who 'entered' agroforestry through work on the dynamics between trees and soils and who realized, but never had time to work on, the management potentials that lie in these dynamics. This book by Anthony Young is, without doubt, a landmark review on tropical land management. Its impact on our level of knowledge and understanding of the potential of agroforestry to achieve the sustainable use of tropical soils will be considerable.

The idea for this book originated in 1981. The intention was that it should be one of five reviews aimed at using existing knowledge to analyse in depth the potential of agroforestry to address problems of particular interest to scientists and specialists in traditional land-use disciplines. The other reviews were meant to deal with the potential of agroforestry to increase food, fuelwood and fodder production, respectively, and to assess the socio-economic potentials of agroforestry. Behind the decision to incorporate these reviews in ICRAF's programme of work lay the conviction that the potential of agroforestry for developing the productivity, sustainability and diversity of small-scale farming systems needed to be demonstrated in an authoritative, scientific fashion to specialists in different disciplines.

Most of these specialists—such as agriculturalists, animal scientists, foresters and economists—had reacted rather coolly to the enthusiastic, but normally completely non-quantified, claims by early promoters of agroforestry, that if you only planted any kind of tree, anywhere, all kinds of miracles would occur. At ICRAF, we saw it as a matter of urgent priority to establish a soundly based scientific foundation for the discipline of agroforestry. The reviews were one means to achieve this.

Development in the field of agroforestry has been rapid since the early 1980s. Today, there is little need to promote agroforestry to a doubtful scientific and development community. The rapidly expanding interest in agroforestry in recent years, witnessed by a myriad of research and development activities, leaves no doubt that agroforestry as an approach to land development is now accepted by most, if not all, disciplinary scientists and development specialists. Increased concern at the highest international policy levels about the sustainability of agricultural development, in the light of the apparent rapid depletion of the natural resourcs-base, has brought agroforestry even further into the limelight.

At the very heart of the question of sustaining agricultural production is the problem of soil conservation. This book provides the most authoritative analysis available up to now of the various hypotheses that trees and shrubs, if properly chosen and managed, have a potential to conserve the soil's productive capacity. Soil conservation is not seen in its traditional, narrow sense of preventing water and wind erosion, but in the broader and much more important sense of maintaining soil fertility. It was written by a scientist for a scientific and technical audience, explaining clearly what we know about tree-soil relations, what are reasonably well founded hypotheses calling for further research, and what is plain speculation or misconception. The main value of this book is that it brings together a substantial amount of information from fundamental research, applied research and observations of real farm and forest conditions.

Anthony Young and all those who have been involved in this undertaking are to be congratulated for this significant contribution to the field of agroforestry.

Bjorn Lundgren
January 1989

PREFACE

This book presents the results of an ICRAF review of the potential of agroforestry for soil conservation, treated in its wider sense to include both control of erosion and maintenance of fertility. Partial results and summaries have already appeared in 20 publications. The present text is intended primarily for research scientists, and gives the evidence on which conclusions are based in some detail. Shorter summaries of results for other groups of readers will be prepared.

Completion of the review has been a task far larger than initially foreseen, involving the appraisal of large areas of soil science in order to assess their significance for agroforestry. It might have become an Augean task if the attempt had been made to include discussion of all recent publications as they appeared. By good fortune, publication coincides with the appearance of the journal, *Agroforestry Abstracts,* which will in future provide assistance in keeping abreast of the growing volume of published results.

If agroforestry research succeeds in its current objectives, then in five to ten years time much of the indirect reasoning necessary at present will have been replaced by results of research directly into agroforestry and soil conservation. At the same time, it is hoped that the conclusions of this review, on the high potential of agroforestry as a means of achieving soil conservation and sustainable land use, will progressively become translated into practice, through the design of sound, appropriate, agroforestry systems and their inclusion in the process of land-use planning.

Anthony Young
Nairobi, August 1988

ACKNOWLEDGEMENTS

This review and publication have been supported by a grant from the Swedish International Development Agency.

Several previous studies deserve special mention as providing foundations to the present work. These are the review of soil productivity aspects of agroforestry by P.K.R. Nair (1984), that of erosion under agroforestry systems by K.F. Wiersum (1984), and work on the effects of erosion on soil productivity by M. Stocking and associates, P.A. Sanchez was the first to state, and appraise, the general soil-agroforestry hypothesis. Information and ideas gained at meetings of the Tropical Soil Biology and Fertility programme have been of great value.

Colleagues at ICRAF have been extremely helpful. Three I should like particularly to thank are Peter Huxley, from whom originated a number of ideas which I have not hesitated to use; Peter Muraya, for his sustained interest, analysis and efficient programming of the SCUAF computer model described in Chapter 15; and Richard Labelle, who has greatly assisted through his identification of those publications which, although not about agroforestry, have significant implications for it. P.M. Hotten and R.J. Cheatle assisted in the development of the SCUAF model.

Many people have kindly offered constructive comments on the draft version published as ICRAF Working Papers, including H.G. Fehlberg, N. Hudson, C.J. Paskett, D. Sanders, T.F. Shaxson, B.R. Trenbath and colleagues at ICRAF. I am grateful to authors who have granted permission to make us of work as yet unpublished, acknowledged by 'in press' citations.

Finally, I should like to thank my wife, Doreen, for her voluntary, but professional, editing of successive drafts, Jane Waweru for her skill, care and patience in preparing the typescript and tables and Sidney Westley for her amiable, but meticulous, editing of the final text.

All photographs are by the author.

Part I. Soil Conservation and Agroforestry

Chapter 1
Introduction

Objectives

This book is a review of the potential of agroforestry for soil conservation, treated in its wider sense to include both control of erosion and maintenance of fertility. The objectives are:

1. To summarize the present state of knowledge on agroforestry in soil conservation, including both known capacity and apparent potential.
2. To indicate needs for research if this potential is to be fulfilled.

The review is primarily directed at scientists engaged in, or about to embark upon, agroforestry research, particularly those in less-developed countries for whom library facilities and other opportunities for access to recent work are limited. Since interdisciplinary cooperation is essential in agroforestry design, both soil specialists and scientists from other disciplines will be involved.

The intention is to provide a summary which will serve as a starting point for further work, including both fundamental research into relations between soils, plants and environment, and applied research directed at the development of practical agroforestry systems for specific regions.

A second intended audience consists of those concerned with planning agroforestry development in national and international development organizations and aid agencies. For these, the review may help to indicate the degree to which agroforestry has the potential to assist in the solution of problems of soil degradation, the range of agroforestry practices available for this purpose, and how and why they are effective. The reader in a hurry will find a summary of results beginning on page 233.

Previous reviews

Farmers have always grown trees on their land, some no doubt with a shrewd idea that this had useful effects on the soil and crop yields. In scientific publications, the first recognition that trees benefit soils came in accounts of the ecological stability of shifting cultivation, provided there was an adequate ratio of forest fallow to cropping (e.g. Gourou, 1948; Nye and Greenland, 1960).

There were isolated instances of those whom, in retrospect, we can recognize were ahead of their time in appreciating the possibilities of integrating trees with farming systems. Thus Leakey, writing of highland Kenya in 1949, advocated rows of trees along contours to control the (already serious!) problem of soil erosion; whilst in 1950, Dijkman wrote of '*Leucaena*—a promising erosion-control plant'. For many years, reclamation forestry has been practised as a means of improving degraded land, notably in India.

More widespread scientific recognition awaited the emergence of agroforestry as a scientific discipline from the late 1970s onwards. Two landmarks were the first symposium to be held by the International Council for Research in Agroforestry (ICRAF), *Soils research in agroforestry* (Mongi and Huxley, 1979), which drew upon experience from other kinds of land use and assessed its significance for agroforestry; and the review, *Soil-productivity aspects of agroforestry* (Nair, 1984, 1987a), in which the main agroforestry systems, traditional and modern, were assessed with special reference to soil aspects. The latter forms a foundation for the present review.

Other accounts of soil conservation in agroforestry include the following:

- *Surface erosion under various tropical agroforestry systems* (Wiersum, 1984); a review of rates of water erosion.
- *Tree crops as soil improvers in the humid tropics* (Sanchez et al., 1985); covering both forest plantations and agricultural plantation crops.
- *Agroforestry for soil conservation* (Lundgren and Nair, 1985); sets out the interdependence of erosion control and fertility maintenance, and the capacity of agroforestry systems to combine these with production.
- *Increasing the productivity of smallholder farming systems by introduction of planted fallows* (Prinz, 1986); a thought-provoking comparison of tree fallows with spatially based agroforestry systems.
- *Amelioration of soil by trees* (Prinsley and Swift, 1986); a symposium.
- *Ecological aspects of agroforestry with special emphasis on tree-soil interactions* (Wiersum, 1986); a set of 'lecture notes'.
- *Soil productivity and sustainability in agroforestry systems* (Sanchez, 1987).

The above accounts have been freely drawn upon in the present review, which was published in draft form as three ICRAF Working Papers, covering respectively control of erosion, maintenance of fertility, and a computer model to predict both (Young, 1986a, 1987a; Young et al., 1987).

The environmental basis

The relations between agroforestry and soil conservation vary with climate, soil type and landforms. To provide a common frame of reference, the terms used are taken from the generalized classification level of the ICRAF

Environmental Data Base (Young, 1985a,1989b). A comparative review of environmental classification systems will be found in Young (1987e).

Climatic zones

For climatic zones (Table 1), the starting point is the 'three worlds of the tropics': the humid tropics (rain forest zone), subhumid tropics (savannas) and the semi-arid zone (sometimes called the sahel). These are defined in terms of Koppen climatic classes. Because the subhumid zone covers a wide range of rainfall, it is subdivided into moist and dry subzones, drought being a serious problem only in the latter. Bimodal rainfall means climates with two distinct rainy and dry seasons.

In terms of vegetation, the boundary between humid and subhumid tropics occurs where closed forest gives place to open deciduous woodland or savanna. That between the subhumid and semi-arid zones corresponds to the replacement of broadleaf deciduous savanna by narrow-leaved, usually thorny, trees and shrubs.

It may be noted that what is here called the dry subhumid zone is elsewhere sometimes included as part of the semi-arid tropics.

Table 1. *Climatic zones.*

Climate and vegetation zones	Koppen classes included	Approximate Rainfall (mm)	Approximate Dry months months (<60 mm)
Humid tropics (rain forest zone)	Af,Am	>1500	4
Subhumid tropics (savanna zone)	Aw,Cw	600-1500	4-8
Moist subhumid		1000-1500	
Dry subhumid		600-1500	
Semi-arid zone	BS	250-600	8-10
Arid zone	BW	<250	11-12
Mediterranean zone	Cs	>150	Winter rainfall

Soil types

The generalized soil types (Table 2) are based on the revised legend to the *Soil map of the world* prepared by the United Nations Food and Agriculture Organization (FAO), commonly called the FAO classification (FAO/ UNESCO (United Nations Educational, Scientific and Cultural Organization), 1974; FAO, 1988). Ferralsols and acrisols are strongly leached

Table 2. *Soil types.*

FAO class (FAO, 1988)	Approximate equivalent, US soil taxonomy (USDA, 1975)	Description
Ferralsols	Oxisols	Highly weathered red and yellow soils, iacking an argic horizon
Acrisols	mainly Ultisols	Strongly leached red and yellow soils with an argic horizon, mainly found in the humid tropics
Lixisols, mainly ferric	Alfisols, mainly ustalfs	Moderately leached red and yellow soils with an argic horizon, mainly found in the subhumid tropics
Nitisols	(no equivalent)	Strongly structured red soils developed from basic parent materials
Calcisols	Calci-great groups	Soils containing free calcium carbonate accumulation
Vertisols	Vertisols	Black, cracking clays

Note: In the earlier legend (FAO/UNESCO, 1974), lixisols were known as luvisols, nitisols were nitosols, and calcisols were calcic units of other primary classes, particularly xerosols; the argic horizon was previously the argillic horizon (its present name in the US taxonomy).

acid soils typical of the humid tropics, acrisols being those with an accumulation of clay in the B horizon. Lixisols are typical of freely drained sites in the subhumid tropics (these were formerly called ferric luvisols, see note to Table 2). The generally more fertile nitisols are found on rocks of basic composition in both humid and subhumid zones.

There is one group of soils which is highly distinctive yet is not satisfactorily recognized by international classification systems. These are the highly weathered sandy soils derived from felsic (granitic) rocks on gently sloping plateau sites in the subhumid zone, variously known as leached pallid soils, weathered ferallitic soils, 'plateau sandveld soils' (Africa) and 'cerrado soils' (South America). The term plateau sandveld soils will be used here.

Calcisols, soils with an horizon of accumulation of free calcium carbonate, are typical of the semi-arid zone. Vertisols are most common on sites with impeded drainage in the semi-arid zone, but may be found on flat, poorly drained land under subhumid and occasionally humid climates.

Landforms

In discussing soil erosion it is convenient to refer to *slope or landform classes* (Table 3), where the terms steep, moderate and gentle may refer to individual slopes or to landscapes in which such slopes are predominant. It has also become common to recognize *sloping lands* (steep lands), dissected or hilly areas dominated by moderate to steep slopes in which erosion is a basic problem.

Table 3. *Slope and landform classes (FAOIUNESCO, 1974; Young, 1985a).*

Class	Explanation	Degrees	Percent
Steep	Dominant slopes	>17°	>30%
Moderate	Dominant slopes	5°-17°	8-30%
Gentle	Dominant slopes	<5°	<8%
Flat	Dominantly level depositional landforms, e.g. flood plains		

Arrangement of the text

It is a basic tenet of this review that the control of soil erosion is only one aspect of soil conservation. In practical development planning, it should not be treated in isolation, but integrated with maintenance of soil fertility and other aspects of agricultural improvement.

However, erosion control is a prerequisite for other forms of conservation; whilst from a scientific point of view, it presents a distinctive set of problems and potential solutions. The potential of agroforestry for control of erosion is therefore treated separately, in Part II.

Where erosion is not a serious problem, or has been brought under control, soil conservation consists of preventing physical, chemical and biological degradation of the soil. The role and potential of agroforestry for this is discussed in Part III.

In Part IV, erosion control and fertility maintenance are integrated in a computer model for the prediction of both. This part also includes a discussion of research needs and a conclusion on the potential of agroforestry for soil conservation.

Chapter 2
Soil Conservation and Sustainability

Soil conservation

Soil conservation is interpreted here in its broader sense to include both control of erosion and maintenance of fertility.

Two policy trends have contributed to this view. First, soil conservation was formerly equated with erosion control. This attitude is still to be found in places; it leads to planning measures and projects in which erosion is thought of in terms of loss of soil material, and its control is treated in isolation from other aspects of agricultural improvement. It is now recognized that the principal adverse effect of erosion is lowering of fertility, through removal of organic matter and nutrients in eroded sediment.

The second trend is the recognition of forms of soil degradation other than erosion, the various kinds of physical, chemical and biological degradation sometimes grouped as decline in soil fertility. It is now recognized that there can be serious soil-degradation problems even in areas where erosion is not a problem, and that it is part of the task of soil conservation to address these.

This leads to the view that the primary objective of soil conservation is maintenance of fertility. To achieve this, control of erosion is one necessary, but by no means sufficient, condition. Equally important is maintenance of the physical, chemical and biological properties, including nutrient status, which together lead to soil fertility.

SOIL CONSERVATION

Soil conservation = maintenance of soil fertility
which requires:

- control of erosion
- maintenance of organic matter
- maintenance of soil physical properties
- maintenance of nutrients
- avoidance of toxicities.

A broader field is that of soil and water conservation, since reduction in water loss through runoff is an integral part of soil conservation. In turn, soil and water conservation form part of the wider aim of the conservation of natural resources, which covers also the conservation of other resources, including vegetation (forests, pastures) and wildlife.

Desertification is a term that has been widely misused. Properly applied, it refers to irreversible, or slowly reversible, reduction in the productive capacity of the environment in the semi-arid zone. The main symptom, and direct effect on productivity, is impoverishment of the vegetation (both total biomass and composition). Low biomass, however, is commonly caused by drought, and will recover by natural processes if there is no other form of degradation. It is where soil erosion has also become serious that the power of recovery of the plant cover is reduced, and the structure can be correctly referred to as desertification (Young, 1984b; Baumer, 1987; Dregne, 1987).

Sustainable land use

Sustainability, as applied to land use, is a more general concept than either soil and water conservation or the conservation of natural resources as a whole, and has been variously defined. Its essential feature is the link between conservation and production. Sustainable land use is that which achieves production combined with conservation of the resources on which that production depends, thereby permitting the maintenance of productivity. Expressed as a pseudo-equation:

SUSTAINABILITY = PRODUCTIVITY + CONSERVATION OF RESOURCES.

For a land-use system to be sustainable requires conservation not only of soil but of the whole range of resources on which production depends. Harvesting of forests must not exceed rates of regrowth, for example, and there are wider considerations such as that of land tenure. However, the most direct and primary requirement for sustainability is to maintain soil fertility.

Besides being obviously true for arable cultivation, this applies also to land-use systems based on grazing. Drought, or short periods of over-grazing, can lead to temporary degradation of pasture resources, but these may recover. The degradation becomes irreversible, and is thus correctly described by the (often misused) term desertification, if over-grazing is allowed to continue to the point at which soil degradation sets in.

The objective of sustainable land use is the continuation of production over a long period—that covered by the planning horizons of planners and farmers, usually about 20 years, occasionally up to 50. Given the current food shortage in the less-developed world, and the virtually inevitable population increase, the present call is for forms of land use that will not only allow maintenance of current levels of production, but will sustain production at higher levels than at present.

Chapter 3
Agroforestry

Definitions

Agroforestry refers to land-use systems in which trees or shrubs are grown in association with agricultural crops, pastures or livestock, and in which there are both ecological and economic interactions between the trees and other components. Its essential nature is that it covers combinations of trees with plants or animals, and that there must be interactions between the tree and non-tree parts of the system. It is the ecological interactions that are the most distinctive feature, and which differentiate agroforestry from social forestry (forestry carried out by communities or individuals), although there is a large overlap.

Some amplifications are needed to convert the above description into a formal definition. All woody perennials, including palms and bamboos, are included under trees and shrubs; the association between the woody and non-woody components may be a spatial arrangement, a time sequence, or a combination of these; whilst 'and/or' should be understood for 'or'. This leads to the formal definition:

> **AGROFORESTRY**
> Agroforestry is a collective name for land-use systems in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) and/or livestock in a spatial arrangement, a rotation or both, and in which there are both ecological and economic interactions between the tree and non-tree components of the system.

The main *components* of agroforestry systems are trees and shrubs, crops, pastures and livestock, together with the environmental factors of climate, soils and landforms. Other components (e.g. bees, fish) occur in specialized systems.

An *agroforestry practice* is a distinctive arrangement of components in space and time. An *agroforestry system* is a specific local example of a practice, characterized by environment, plant species and arrangement, management, and social and economic functioning. There are hundreds, possibly thousands, of agroforestry systems but only some 20 distinct practices.

The range of agroforestry practices

Whereas the existence of agroforestry is now widely recognized among planners and development agencies, it is not always appreciated how many different kinds of land-use practice are included within it.

Table 4 is a classification of agroforestry practices. It is given first to illustrate the range of practices, and secondly as a basis for discussion in the succeeding text.

Table 4. *Agroforestry practices.*

MAINLY AGROSYLVICULTURAL (trees with crops)
- Rotational:
  - Shifting cultivation
  - Improved tree fallow
  - Taungya
- Spatial mixed:
  - Trees on cropland
  - Plantation crop combinations
  - Multistorey tree gardens
- Spatial zoned:
  - Hedgerow intercropping (barrier hedges, alley cropping) (also agrosylvopastoral)
  - Boundary planting
  - Trees on erosion-control structures
  - Windbreaks and shelterbelts (also sylvopastoral)
  - Biomass transfer

MAINLY OR PARTLY SYLVOPASTORAL (trees with pastures and livestock)
- Spatial mixed:
  - Trees on rangeland or pastures
  - Plantation crops with pastures
- Spatial zoned:
  - Live fences
  - Fodder banks

TREE COMPONENT PREDOMINANT (see also taungya)
- Woodlots with multipurpose management
- Reclamation forestry leading to multiple use

OTHER COMPONENTS PRESENT
- Entomoforestry (trees with insects)
- Aquaforestry (trees with fisheries)

At the highest level, the classification is based on the components present: trees with crops, trees with pastures, practices in which the tree component is dominant and practices involving special components. The second level is based on the spatial and temporal arrangement of components. *Rotational practices* are those in which the association between trees and crops takes place primarily over time, whilst *spatial practices* are those in which it is primarily a combination in space. Spatial systems are divided into mixed and zoned. In *mixed spatial practices,* the trees and herbaceous plants are grown in intimate mixtures, with the trees distributed over more or less the whole of the land area. In *zoned spatial practices,* the trees are either planted in some systematic arrangement, such as rows, or are grown on some element in the farm, such as boundaries or soil conservation structures. The third level of classification employs detailed spatial arrangement and functions as criteria.

Considered as a basis for research, sylvopastoral practices and those with special components are clearly distinct, requiring facilities for research into pasture and livestock or other specialized aspects. The remaining groups differ in the nature and extent of tree/crop or tree/pasture interactions. In purely rotational systems, the interaction takes place mainly through inheritance of soil changes. In spatial-mixed systems, the tree/crop interface is distributed over all or much of the land management unit, whereas in spatial-zoned systems it occupies defined locations.

Part II. Agroforestry for Control of Soil Erosion

Chapter 4
Trends in Soil-Conservation Research and Policy

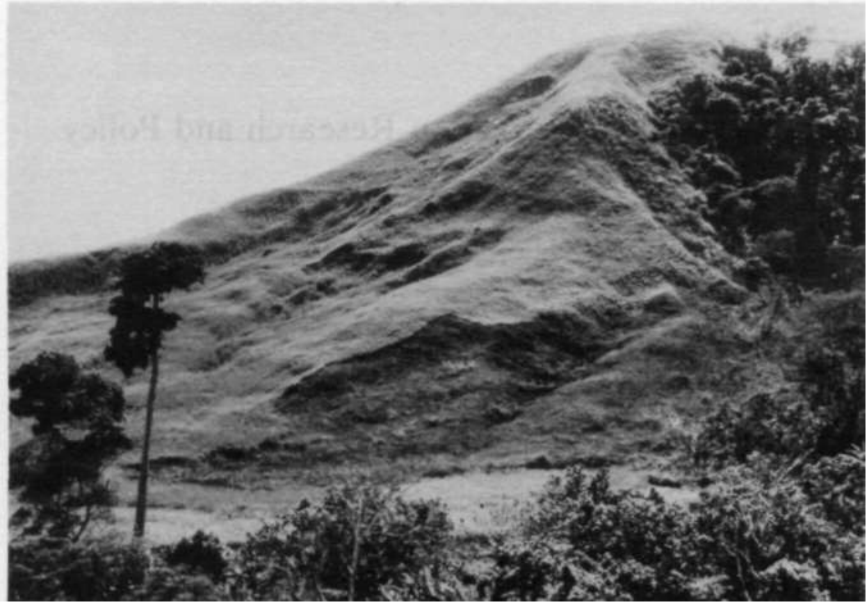
Evidence from direct experimental observations on erosion under agroforestry systems is limited. As in most branches of agroforestry research, however, there is much to be learnt from taking the results of research based on agricultural and forest land use and applying them to agroforestry.

This discussion is therefore divided into two sections. This chapter is a review of recent trends and the present state of knowledge in erosion research and conservation policy as a whole, noting points of significance for agroforestry. Chapter 5 summarizes the limited available experimental evidence, and Chapter 6 consists of a review of agroforestry practices in relation to soil conservation, using both direct evidence and hypotheses of likely effects based on the preceding review.

Awareness of the need for soil conservation

Awareness of the need for soil conservation arose in the United States of America (USA) in the 1930s. There had been many cases of irreversible soil loss by erosion before that time, perhaps as early as pre-classical times in the Mediterranean lands. Severe erosion occurred both in indigenous communities, as a result of increase in population and hence cultivation intensity, and following settlement of tropical lands by Western immigrants. Examples are chronicled in a milestone of erosion awareness, *The rape of the earth* (Jacks and White, 1939).

In the tropics, descriptions of erosion and its consequences date from the 1930s and 1940s. Examples are accounts of erosion in Nigeria (Ainslie, 1935), Trinidad (Hardy, 1942) and a review, *Soil erosion in the British colonial empire* (Stockdale, 1937). In his monumental *African survey* (1938), Hailey devoted no less than 60 pages to erosion, remarking that it is 'now one of the most serious problems of Africa'. As a consequence, soil conservation became part of the agricultural policy of the colonial powers, continuing as such through the 1950s. A notable example was Zimbabwe (then Southern Rhodesia) where conservation practices imported and adapted from the USA were widely applied.



1. The problem of sloping lands: steep slopes, cleared of forest for cultivation. Guadalcanal, Solomon Islands.

2. Soil erosion as usually conceived: gullying in valley-floor grazing land. Dedza, Malawi.

3. The more widespread form of erosion: sheet erosion where steep slopes have been cultivated. Butare, Rwanda.

Whilst soil-conservation specialists never wavered in their advocacy, governmental awareness and policy emphasis declined in the 1960s. This coincided with the post-independence period in ex-colonial territories, where conservation was for a time associated with 'colonialist' policies and thus could not immediately be given a prominent place on the development agenda. Meanwhile, rising rates of population increase were leading to the frequent extension of cultivation onto steep slopes and other vulnerable land.

From the mid-1970s onwards, there has been a revival of awareness of soil conservation, and of attention to it in development policy. If any single factor can be held responsible, it is the continuing increase in pressure upon the land, the disappearance in most countries of substantial areas of new land for settlement and thus a growing appreciation of the dependence of production on land resources.

A landmark was the formulation of the World Soil Charter by FAO (1982), coupled with increased emphasis on erosion control in FAO policy. More recently, the World Bank has given greater attention to environmental aspects of development. Adoption of conservation policies by governments has naturally been variable but, as a generalization, it has increased over the past 10 years and is still growing. Looking to the future, a recent review of factors affecting land resources and their use over the next 50

4. Trees alone do not prevent erosion: a *Eucalyptus* plantation. Rwanda.

years lays much stress on the need to control soil degradation (Young et al., 1987).

In the scientific field, the increased attention has been reflected in a flood of symposia and reviews, on erosion in general and in the tropics in particular. These include:

- Greenland and Lal, 1977 (28 papers). On conservation in the tropics. A scientific landmark, with emphasis on the importance of land cover.
- FAO, 1977 (16 papers). Papers range from erosion measurement and conservation practices to watershed management, research needs and conservation extension.
- De Boodt and Gabriels, 1978 (85 papers). On erosion research in general, with emphasis on measurement of rates.
- Kirby and Morgan, 1981. Not a symposium but a multi-authored book, with a focus on the mechanisms of processes.
- Morgan, 1981 (42 papers). Possibly the best symposium volume to date, for its all-round coverage of topics, ranging from technical aspects to policy.
- Kussow et al., 1982 (8 papers). On erosion and conservation in the tropics.
- Hamilton and King, 1983. Originated as a symposium, but synthesized into a book. Covers hydrologic and soil responses to the conversion of watersheds from natural forest to other land uses: forest plantations, pastures, agricultural tree crops, annual crops, agroforestry.
- Lal, 1984. A review of erosion control in the tropics.
- O'Loughlin and Pearce, 1984 (49 papers). Effects of forest land use on erosion and slope stability (landslides).
- El-Swaify et al., 1985 (85 papers). Covers erosion measurement, effects of production, methods of prediction, the implementation of conservation programmes and conservation policy.
- Craswell et al., 1985 (18 papers). A regional symposium, with examples drawn particularly from the Philippines and Asia.
- Follett and Stewart, 1985. A symposium on soil erosion and crop productivity,
- Lal, 1988 (10 papers). Methods of erosion research, including field measurement and modelling.
- Moldenhauer and Hudson, 1988 (32 papers). A symposium of particular value for discussions of conservation policy.
- Proceedings of the 4th International Soil Conservation Conference, Maracay, Venezuela, 1985, and of the 5th Conference, Bangkok, 1988, to be published.

In addition there have been reports from a number of national soil-conservation conferences, for example three in Kenya.

Trends in research and policy

The traditional approach

The earlier or traditional approach, as practised by soil-conservation or land-husbandry departments, is set out in standard texts and handbooks. Most textbooks were directed at US conditions, but that of Hudson (1981) is a clear summary, with a focus on the tropics, which has stood the test of time. Handbooks are texts directed at the design of soil-conservation measures in the field. Examples are FAO (1965), CTFT (Centre technique forestiere tropicale) (1979), Leblond and Guerlin (1983), Weber and Hoskins (1983a) and Hudson (1987), together with many national handbooks, for example those for Kenya (Wenner, 1981) and India (Singh et al. 1981b).

The following is a summary of features of the traditional approach. Whilst it may be selective, to point out the contrast with recent trends discussed below, it is not intended as a parody! Features are:

1. Most attention was given to erosion of croplands, much less to that of grazing lands.
2. Attention was focused on rates of soil loss, as tonnes per hectare/tons per acre; as a consequence:
    a. research was directed mainly at measuring rates of soil loss;
    b. conservation measures were directed at reducing the rate of soil loss; in the USA, the aim was to design conservation measures which supposedly brought the rate below a specified level, called 'tolerable erosion', although not many countries followed this practice of setting a target figure.
    c. attempts to assess the consequences of erosion for productivity, and hence economic analysis, were directed at the effects of reduction in soil depth.
3. The requirements of arable cropping with respect to soil cover were taken as fixed and unalterable; hence conservation works were directed at reducing runoff or breaking the force of downhill flow. This will be referred to as the barrier approach to conservation.
4. Land-capability classification was widely employed as a basis for land-use planning. The approach originated in the USA (Klingebiel and Montgomery, 1961) and was adapted for many tropical countries, for example in Africa, first by Zimbabwe (Conex, 1960) and subsequently Malawi (Shaxson et al., 1977) and Zambia (Zambia, Department of Agriculture, 1977). In this approach only land below a certain angle (depending on rainfall and soil type) is classified as suitable for arable use, primarily on grounds of erosion hazard. All steeper land should be used for grazing, forestry or recreation and conservation.
5. Extension was conducted on the basis that soil conservation should come first, as a necessary prerequisite for other agricultural improvements.

As a result, conservation projects or campaigns were sometimes conducted in isolation, not linked to increases in productivity.
6. Extension work in soil conservation was often conducted on the basis of a prohibitive policy, either by refusing to allow cultivation of land deemed to have a high erosion hazard, or by compulsory, legally enforced requirements for the construction of conservation works.

Some successes were achieved through implementation of this approach, notably in Zimbabwe. Frequently, however, problems arose in applying it to the typical situation in less-developed countries, that of small farms, high land pressure and low capital resources both of farmers and government. Among these problems were:

- It was often found impracticable to reduce erosion to the supposedly desirable limits.
- The costs, or labour requirements, of the physical works necessary to control runoff by such means as bunds and terraces were commonly found to be excessive. Where such works were constructed by mechanical means (with foreign aid), these were not always maintained (e.g. Mwakalagho, 1986; Heusch, 1986; Reij et al., 1986).
- The results of land-capability classification could not be applied. Through land pressure, moderate and steep slopes were already under cultivation, and it was economically, socially and politically unacceptable to require that these should be abandoned. A way had to be found to make such cultivation environmentally acceptable.
- Conservation extension did not work. On the one hand, it was found impossible to enforce a prohibitive policy. On the other, the cooperation of farmers could not be obtained unless they could see a benefit from soil conservation in terms of higher crop yields; when conservation is carried out in isolation from other agricultural improvements, no such benefits occur.
- Using conventional methods of economic analysis, in particular with time-discounting of benefits, coupled with an approach based on loss of soil depth, it was often hard to justify conservation in economic terms.

Recent trends

Changes to the earlier policy have come about through advances both in natural and social science. These recent trends are as follows:

1. Erosion is regarded as one of a number of forms of soil degradation, including deterioration of physical, chemical and biological properties, all of which require attention (FAO, 1978, 1979).
2. Arising out of the need to justify conservation in economic terms, research effort has been directed to assessing the effects of erosion on soil properties and crop productivity. Specifically:

a. It has been recognized that the consequences of erosion are by no means limited to loss of soil depth; its major adverse effects are loss of organic matter and plant nutrients, with consequent degradation of soil physical properties and decline in crop yields (cf. papers in Greenland and Lal, 1977; Lal and Greenland, 1979; Rijsberman and Wolman, 1985).

b. Experimental work has been carried out on the effects of erosion on crop yields. At first this was attempted mainly by means of artificial-desurfacing experiments. Later it was found that this method underestimated the yield reductions caused by erosion (Lai, 1983,1984; Stocking, 1984; Stocking and Peake, 1986; Peake, 1986).

3. There is a greater emphasis on the effects of soil cover as a means of controlling erosion, as compared with checking runoff. This arose in part out of experiments directed initially at the effects of mulching, and subsequently from work on minimum tillage (papers in Greenland and Lal, 1977).
4. It has become accepted that cultivation will continue on many areas of sloping land, and that ways must be found of making such use environmentally acceptable. Sloping lands, areas in which moderate and steep slopes are predominant, have become recognized as an identifiable type of environment with a set of distinctive problems (Luchok et al., 1976; Novoa and Posner, 1981; Siderius, 1986).
5. In extension, it is recognized that a prohibitive policy does not work, and conservation must be achieved through the willing cooperation of farmers. To do this, farmers must be motivated through being able to see benefits from conservation works. It follows that soil conservation should be introduced as part of an improved farming package, which will result in an immediate rise in crop yields or other benefits (e.g. Queblatin, 1985, Shaxson et al., 1989).
6. In drier environments, there is greater integration between soil and water conservation. Conservation works are designed to achieve both. Farmers may be led to adopt soil conservation if they can see that it leads at the same time to water conservation and thus improved yields (e.g. El-Swaify et al., 1984).
7. There is some recognition of the additional need to control erosion on grazing lands, although the amount of effort directed at this still falls short of its proportional importance (e.g. papers in FAO, 1977; Dunne et al., 1978).

See reviews of soil conservation strategies by Reij et al., 1986; Shaxson et al., 1989; in press; Hudson 1983, 1988 and in press.

Implications for agroforestry

Based on the above trends, implications for agroforestry in relation to soil conservation are:

- The effects of agroforestry on soil-fertility maintenance should be considered jointly with direct effects on erosion control.
- Agroforestry has a potential for erosion control through the soil cover provided by tree canopy and litter, in addition to the role of trees in relation to the runoff-barrier function. This is discussed below.
- The integration of conservation with improved farming in general, coupled with that of securing cooperation of the farmers at an early stage, accords well with the approach of agroforestry diagnosis and design (Raintree, 1987).
- In drier regions, erosion control should also be assessed jointly with the role of trees in water management.
- Sylvopastoral systems should be included when assessing potential for erosion control.

Seen from a broader perspective, the problem of soil erosion is socio-economic as well as environmental and technical. Those who suffer most, the poorer farmers, are least able to undertake the conventional types of measures for its control (Blaikie, 1985; Roose, 1988). The low input costs of many agroforestry systems make them available to poorer farmers.

FEATURES OF SOIL-EROSION RESEARCH AND POLICY

- The major adverse effects of erosion are loss of soil organic matter and plant nutrients, with consequent decline in crop yields.
- The costs or labour requirements of controlling erosion by earth structures are frequently found to be excessive.
- A way has to be found to make cultivation of sloping lands environmentally acceptable.
- Conservation extension by means of a prohibitive policy simply does not work.
- The need to achieve conservation by securing the cooperation of farmers accords well with the approach of agroforestry diagnosis and design.

Predictive models and their significance

Owing to the difficulty of measuring erosion rates, much erosion-control work is based on the used of predictive models. These are equations which have been calibrated by means of measurements of standardized plots, which are then applied to field situations. They are relevant to agroforestry because of the rates of erosion, which indicate factors of significance for the planning of erosion control through agroforestry.

Three models are widely used to predict rates of soil erosion: the Universal Soil-Loss Equation (USLE), the-Soil Loss Estimation Model for Southern Africa (SLEMSA), and the erosion-based parts of the FAO method for soil-degradation assessment (here called the FAO model); in addition, there is a system of some complexity for modelling erosion and deposition processes in detail devised by Rose. There are also computerized models which combine prediction of erosion rates with impact, including CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) and EPIC (Erosion-Productivity Impact Calculator) (Knisel, 1980; Williams, 1985; Flach, 1986; Foster, 1988).

Features of the models

The Universal Soil-Loss Equation (USLE) (Wischmeier and Smith, 1978; for discussion, see Wischmeier, 1976). This is based on a vast amount of experimental data for the USA (15 000 plot-years) and has been calibrated and validated to a much more limited extent for some tropical areas. It is by far the most widely used method, which when calibrated for a given region will predict erosion losses from experimental plots, and thus (it is assumed) from farmland under similar treatments, to a level of accuracy sufficient for land-use planning purposes. The equation is designed to predict erosion for a specific site, such as a field.

The USLE predicts soil loss, A, as t/ha/yr, by the effects of six factors multiplied:

$$A = R \times K \times L \times S \times C \times P .$$

There is no intrinsic reason why the effects of individual *causes* should be multiplicative; the variables are calibrated in such a way that this relation will hold.

R, the *rainfall factor*, is the product of the energy contained in rain storms multiplied by their maximum 30-minute intensity for all storms of more than 12.5 mm; it is also called the EI_{30} index. Calculation of the R factor requires examination of detailed rainfall-intensity records in the first instance, following which, isoerodent maps can be drawn up. Where neither data nor maps are available, several studies have shown that in the tropics a rough approximation can be obtained by taking half the value of mean annual rainfall in millimetres, usually somewhat less (Roose, 1976, 1977b; Babu et al., 1978; FAO, 1979; Singh et al., 1981a; Lo et al., 1985). Thus a site in the rain-forest zone with 2000 mm rainfall has an R factor in the region of 800-1000, one in the dry subhumid zone with 800 mm rainfall an R factor of about 300-400.

K, the *soil erodibility factor*, describes the resistance of the soil to erosion. It is set such that the product (R x K) gives the soil loss rate on bare soil on a standard erosion plot, in tonnes per hectare. A standard plot is 22 m long with a uniform 9% (5.14°) slope. (In using data, it is essential to make sure that the values of the R and K factors are compatible; namely, either both metric and giving erosion as tonnes per hectare, or both non-metric and giving erosion as short tons per acre.)

K = 1.0 where A = R, i.e. soil loss is equal to the rainfall factor, and K = 0 for a hypothetical totally resistant soil. The K value for a given soil is found out by experiment, such that it gives the soil loss when multiplied by R. Typical values are 0.1 for more resistant tropical soils (e.g. ferralsols with stable micro-aggregation), 0.3 for soils of intermediate nature (e.g. ferric lixisols) and 0.5 or more for highly erodible soils.

L, the *slope length factor,* gives the ratio of soil loss from the length of the field for which erosion is to be predicted to that on a 22-m plot; the relation is approximately linear, but a doubling of slope increases erosion by less than 50%. S, the *slope steepness factor,* is the ratio of soil loss from a field under consideration to that on a 9% slope; it is given by a quadratic equation, the effect of which is that doubling the gradient more than doubles the rate of erosion. In practice, these are combined as a single *topographic factor,* LS (Table 5). Most of the experimental data for the USLE are from gently to moderately sloping plots, the quoted values for steep slopes being partly extrapolations.

C is the *cover and management factor* (or cover factor), giving the ratio of soil loss from a specified crop cover and management to that from bare fallow. It is obtained by detailed measurements of crop cover at different times of year, but tables of typical values are available. C = 1 for bare fallow and falls close to zero for complete cover throughout the year.

In practice, C varies over almost the full range of these extremes. For example an overgrazed pasture, or an annual crop with low soil cover such

Table 5, *Values of the topographic factor (LS) in the universal soil loss equation. Based on Wischmeier and Smith (1978).*

Slope		Slope Length (m)		
Percent	Degrees	50	100	200
2	1	0.2	0.3	0.4
4	2	0.5	0.7	0.9
6	3	0.9	1.2	1.7
8	5	1.3	1.8	2.5
10	6	1.8	2.5	3.5
15	9	3.3	4.6	6.5
20	11	5.2	7.5	10.0
25	14	7.5	11.0	15.0
30	17	10.0	15.0	20.0
40	22	16.0	23.0	34.0
50	27	23.0	36.0	45.0

as a low-yielding maize or tobacco, may have a C factor as high as 0.8, meaning that erosion is not much less than on bare soil.

On the other hand, a dense cover crop or perennial crop (e.g. well-maintained tea) can have a C value of the order of 0.01 and natural rain forest as low as 0.001, meaning that erosion is one hundredth and one thousandth as fast, respectively, as on bare soil under the same climate, soil and slope.

P, the *support practice factor,* is defined as the ratio of soil loss with a given conservation practice to that under crops in rows running up and down the slope. It is only meaningful where such practices are standardized and closely defined. For the examples given in the US handbook, practices which leave the slope as it is, such as strip cropping, have P factors of 0.4 or more in most circumstances; that is, they may reduce erosion by about half. Well-maintained terracing can produce P values in the region of 0.1 to 0.05.

The USLE should be used with caution in the tropics, where its predictions do not always seem realistic. Results for humid climates and steep slopes are extremely high; for example, cereal cultivation on a 20° slope in the humid tropics leads to values of the order of R = 1000, K = 0.2, LS = 16 and C = 0.4, giving a predicted erosion of 1280 t/ha/yr, or about 10 cm of soil thickness.

The most significant feature of this model is the very high potential for reducing erosion by management practices which lead to greater soil cover.

The Soil-Loss Estimator for Southern Africa (SLEMSA) (Elwell, 1980, 1981; Stocking and Elwell, 1981; Stocking, 1981). The model has the same objective as the USLE, to predict erosion at a specific farm site, as a basis for land-use planning. It was designed and calibrated specifically for southern Africa, and has been adapted to the mapping of erosion hazard over large areas (Stocking, 1987).

Soil loss, Z, in t/ha/yr, is given by the equation:

$$Z = K \times C \times X.$$

K is the soil loss from bare soil on a standard plot 30 m long with a 4.5% (2.6°) slope. It is derived from an equation in which the variables are E, the rainfall energy in J/m^2, and F, the soil erodibility index.

C is the crop ratio, which adjusts soil loss from a bare fallow to loss under the crop grown. C is a function of i, the percentage of rainfall energy intercepted by the crop cover. When even 20% of rainfall energy is intercepted, the value of C is reduced to 0.3, whilst with 40% energy intercepted, C becomes 0.1 and at 50%, about 0.05.

X, the topographic ratio, is a function of S, slope steepness, and L, slope length. Its values are very similar to those of the LS factor in the USLE.

Thus there are 5 basic control variables: E, rainfall energy, F, soil erodibility, i, energy interception by the crop, S, slope steepness, and L, slope length. These give rise to three intermediate variables, K, soil loss from bare soil, C, the crop ratio, and X, the topographic ratio, which are then multiplied to give the predicted erosion loss.

This model differs from the USLE in that the four physical systems that affect erosion, namely climate, soil, crop and topography, are treated as separate entities; and land use or management practice is considered with respect to its effects on each of these systems. However, the relative magnitudes of the different controlling variables are similar to those in the USLE, in particular, the large differences in erosion rate that can be brought about by crop cover.

The FAO model (FAO, 1979, pp. 43-46 and 69). This was devised for the purpose of assessing average water erosion hazard over large areas, as a basis for maps at a continental scale. It is one of a set of methods for assessing soil degradation, the others being methods for assessing wind erosion, salinization, sodication, acidification, toxicity, physical degradation and biological degradation. These were applied to produce maps of northern Africa, showing present degradation (soil degradation believed to be occurring under present land use) and degradation risk (the risk of degradation under the worst possible land use and management).

The method for predicting water erosion is essentially a simplification of the USLE. Erosion loss, A, as t/ha/yr, is given by:

$$A = R \times K \times S \times C$$

where the symbols have the same meanings as in the USLE (the source does not use these symbols; they are adopted in the present text for convenience). To the best of the author's knowledge, the method has not been tested against observed erosion rates.

What is useful is that ways are given of estimating values of the variables for large areas and under circumstances where the more precise data called for by the preceding models are not available. Thus tables are given for:

- soil erodibility values for soil type and textural classes of the FAO-UNESCO Soil Map of the World (Table 6);
- topography ratings for the slope classes of the same map;
- generalized cover factors for cropland, pasture and woodland.

The soil-erodibility factors range from 0.1 to 2.0, the topographic ratings from 0.15 to 11.0. As in the other models, the land-cover ratings show a much higher relative range, from 0.8 under annual crops in areas of seasonal rainfall to 0.006 under woodland with undergrowth and a ground cover of over 80%.

The model of C.W. Rose (Rose et al., 1983; Rose 1985a, 1985b, 1988; Rose and Freebairn, 1985). This is a mathematical model based on hydrologic principles and designed to simulate the sediment flux on soil. It models rainfall detachment of soil, sediment entrainment and sediment deposition. A summary will not be given here, but attention is drawn to

Table 6. *Generalized values of the soil erodibility factor (K) in the universal soil loss equation (based on FAO, 1979, pp. 44—45). Soil types and textural classes are those of the first version of the FAO classification (FAO/UNESCO, 1974).*

Step 1. Erodibility class of soil type.

Low	Moderate	High
Arenosols	Greyzems	Podzoluvisols
Chernozems	Kastanozems	Vertisols
Ferralsols		Xerosols
Histosols		Yermosols
Lithosols		
Nitosols		
Phaeozems		
Rendzinas		
Rankers		
Ferric and Humic Acrisols	Other Acrisols	Plinthic Acrisols
Mollic and Humic Andosols	Other Andosols	
Ferralic and Humic Cambisols	Other Cambisols	Gelic and Vertic Cambisols
Calcaric Fluvisols	Other Fluvisols	Thionic Fluvisols
Calcaric, Humic, Mollic Gleysols	Other Gleysols	Gelic Gleysols
Ferric Luvisols	Other Luvisols Vertic Luvisols	Albic, Plinthic, Vertic
Mollic and Humic Planosols		Other Planosols
Humic and Leptic Podzols		Other Podzols
Calcaric Regosols	Other Regosols	Gelic Regosols

Step 2. Soil erodibility factor.

Erodibility class	Low	Moderate	High
Textural class			
Coarse	0.1	0.2	0.4
Medium	0.15	0.3	0.6
Fine	0.05	0.1	0.2

one feature, namely the treatment of the relation between soil cover and sediment entrainment.

Cover is represented as Cr, the fraction of soil surface exposed, and sediment entrainment efficiency by a non-dimensional factor n. At Cr = 0 (bare soil), n = 0.7, whereas at Cr = 0.9, n falls to 0.25; that is, 'a cover of only 10% reduced soil loss by about two thirds'. The point is further illustrated by a diagram showing sediment concentration against cover. For a slope of 10%, values are:

Cover factor (Cr)	*Sediment concentration (kglm^3)*
1.0 (bare soil)	190
0.9	55
0.5	8
0.3	4
0.0 (100% cover)	1

This reinforces the conclusion from previous models that soil cover is the dominant feature in controlling erosion.

Implications

All the predictive models are based on the same fundamental causes of water erosion: rainfall energy, soil erodibility, slope length and angle, and the land cover provided by plants. What is relevant to erosion control are the relative magnitudes of the effects of each variable upon rate of erosion, the extent to which each variable can be affected by land management, and the cost involved in such control measures.

Rainfall erosivity is beyond the control of man. In very general terms it is twice as high in the subhumid (savanna) zone as in the semi-arid zone, and twice as high again in the humid (rain forest) zone.

Soil erodibility is initially an inherent property of the soil, but can change through response of the soil to management. The main cause is changes in soil organic matter, together with their effects on soil structure and permeability. Based on USLE data, a fall of 1% in soil organic matter alone causes a rise in erodibility of about 0.04 units; if coupled with a deterioration of one permeability class, the change is 0.07 units. Thus a soil with an initial K factor of 0.30 might be changed, if organic matter were degraded by 10%, to one with a K factor of 0.34 to 0.37, a relative change of 13 to 23%. In general terms, moderately severe degradation of the soil organic matter content is likely to lower its resistance to erosion by an amount of the order of 10-25%, severe lowering of organic matter to lower resistance by about 50%.

Slope length and angle in the geomorphological sense are unalterable, but their values with respect to effects on erosion can be modified by conservation measures.

Effective slope angle can be altered only by terracing. Where regularly maintained, this does control erosion on steep slopes. However, the cost of construction (or the labour requirement) is high.

Effective slope length is reduced by conservation measures of the barrier type. These may be earth structures (bunds, storm drains and cutoff ditches) or biological barriers (grass strips, barrier hedges). On relatively gentle slopes, up to about 14% (8°), barriers can be effective in controlling erosion, subject to cost of construction and proper maintenance. On steep slopes, barriers have to be closely spaced if they are to reduce erosion to acceptable levels, e.g. about 5 m apart on a 40% (22°) slope; this means that the proportion of land taken is substantial unless the barriers are narrow.

A distinction should be made between impermeable and permeable barriers. *Impermeable barriers* are those, such as ditch-and-bank structures, which check all runoff, either by diversion or by causing infiltration. *Permeable barriers* are those which allow some proportion of runoff to pass through. In agroforestry, barriers are only impermeable in cases of trees planted on earth structures. Where the barriers are purely biological, such as hedges or grass strips with trees, they are partly permeable.

Most standard soil-conservation findings are based on the assumption of impermeable barriers. Research is needed into the functioning of partly permeable plant-based types of barrier.

Land cover has a large influence on rate of erosion. Whichever of the predictive models is used, if the effects of the rainfall, erodibility and slope factors alone are calculated, high rates of erosion usually result. For example, a site in the subhumid zone (R typically 500), with a ferric luvisol (K typically 0.3) on a 50 m, 10% (5.7°) slope (S = 1.7) will have a predicted erosion of 255 t/ha/yr. Reducing the slope length to 10 m by barrier-type works lowers erosion to 105 t/ha/yr. These apparently high values are predictions, validated by experimental work, of the erosion to be expected if land is left under bare fallow.

The cover factor can dramatically reduce predicted erosion rates (Table 7). For annual crops, the value varies substantially with growth and management. A moderate-yielding cereal crop has a C value of about 0.4, a late-planted, low-yielding one may be 0.8, whilst for a high-yielding crop with mulching, a value as low as 0.1 has been obtained (N.W. Hudson, personal communication). Intercropping generally gives greater cover than monocropping. Perennial tree crops with cover crops beneath can reduce erosion to between 0.1 and 0.01 of its rate on bare soil. There are large differences according to whether residues are applied as surface mulch or burned or buried.

In summary, the combined effects of rainfall, soil erodibility and slope will frequently lead to predicted rates of erosion which are unacceptably high, whilst cereal and root crops do not greatly reduce such rates. On the other hand, any management system in which a substantial soil cover is maintained during the period of erosive rains has the capacity to reduce erosion to between a tenth and a hundredth of its value on bare soil.

Acceptable erosion

It is impossible to reduce the rate of soil loss to zero. Limits have to be set as targets for the design of land-use systems. They need to be set low enough such that there will not be a serious or progressive decline in crop production, yet high enough to be realistically achievable.

Table 7. *Values of the cover factor (C) in the universal soil loss equation.*

A. Based on FAO (1979)

	Percentage ground cover					
	0-1	1-20	20-40	40-60	60-80	80-100
Pasture grassland and rangeland	0.45	0.32	0.20	0.12	0.07	0.02
Woodland with appreciable undergrowth	0.45	0.32	0.16	0.18	0.01	0.006
Woodland without appreciable undergrowth	0.45	0.32	0.20	0.10	0.06	0.01
Crops						
Humid climates	0.4					
Subhumid climates	0.6					
Semi-arid climates	0.8					

fl. *Based on Roose (1977a, 1986) for West Africa*

Bare soil (reference)	1.0
Dense forest	0.001
Savanna in good condition	0.01
Savanna, burnt or overgrazed	0.1
Covercrops	0.01-0.1
Maize, sorghum, millet (as a function of yield)	0.4-0.9
Cotton, tobacco	0.5
Groundnuts	0.4-0.8
Cassava, yams	0.2-0.8
Oil palm, rubber, cocoa with cover crops	0.1-0.3
Pineapple	
residues burnt orburied	0.1-0.5
residues on surface	0.01

C. Based on Lewis (1987) for Rwanda

Coffee	0.02	Potato	0.22
Banana	0.04	Sweet potato	0.23
Banana/beans	0.10	Cassava	0.26
Pasture	0.10	Maize/beans	0.30
Banana/sorghum	0.14	Maize	0.35
Beans	0.19	Sorghum	0.40
Beans/cassava	0.20	Tobacco	0.45

The concept of 'tolerable erosion' or 'soil loss tolerance' has often been misleadingly used. It originated at the time when erosion was viewed primarily as physical loss of soil material. The basic notion was that erosion is acceptable up to the rate at which soil is renewed by natural processes. The view became established that 'where natural processes are speeded up by tillage', about 25 mm of topsoil will form in 30 years. This is equivalent to an erosion of about 5 short tons per acre per year (11.2 t/ha/yr). Another reason for selecting this value was that it is a rate to which it was thought practicable to limit erosion under farming conditions. The US Soil Conservation Service sets limits for tolerable erosion, mainly in the range 2.2-11.2 t/ha/yr, the basis being that shallow soils over hard rock have a lower tolerance than deep soils or those formed from unconsolidated parent materials. In fact, such limits are often not achieved (Smith and Stamey, 1965; McCormack and Young, 1981; ASA, 1982).

The scientific basis of this concept is dubious. It initially referred to the formation of topsoil from already weathered soil material, not the weathering of rock into regolith, but some subsequent discussions confuse these two processes. Geomorphological evidence indicates that typical rates for natural denudation are 50 mm per 1000 years on gentle slopes and 500 mm per 1000 years on steep slopes, varying widely with climate and rock type. It is rarely practicable to reduce erosion on cultivated" or grazing land to these rates (Stocking, 1978; Young, 1969; Saunders and Young, 1983; Young and Saunders, 1986).

The aims of erosion control should be reformulated with more emphasis on productivity decline. The loss of soil volume, or thickness, only becomes serious when erosion has proceeded to an advanced stage. Long before this is reached, serious losses of production occur through erosion of organic matter with consequent decline in soil physical properties and loss of nutrients.

Tolerance limits for soil erosion should be set on the basis of sustained crop yields, translated into terms of maintenance of organic matter and nutrients. Specifically, the capacity of agroforestry practices to supply organic matter and recycle nutrients needs to be integrated with losses of these through erosion, in order to determine whether a system is stable.

Significance for agroforestry

Models are a substitute for reality and experimental data are greatly to be preferred. However, in the practical planning of erosion control using agroforestry, it is simply not practicable to measure rates of erosion and nutrient loss on all field sites. Thus, the main use of erosion-prediction models is to extend results obtained under experimental conditions on a small number of carefully monitored sites to the numerous field sites for which control measures are being planned. For this to be possible, it is necessary to calibrate the models for the conditions of agroforestry, which are not identical to those of control by earth structures.

For agroforestry research and design, features of significance are:

1. On steep slopes, barrier-type structures for erosion control must be closely spaced, about 6 m or less apart. For this to be acceptable to farmers, such barriers must be narrow, productive or both, conditions for which hedgerows offer design potential.
2. Barriers formed by trees, shrubs or hedgerows are partly permeable. Some of the runoff may cross the barriers, whilst the entrained soil will be partly filtered out and deposited. Existing models are not fully applicable until research has been conducted into the magnitude of these processes.
3. Since soil cover can have such large effects in controlling erosion, research in agroforestry should give particular attention to the cover effects obtainable by using prunings from the tree component as mulch.
4. Conversely, a canopy of trees more than a few metres high is not expected substantially to reduce erosion, other than by the litter which falls from it.
5. Research is needed into whether the filtering effect of partly permeable tree and shrub barriers reduces the nutrient enrichment ratio of eroded soil.

In summary, erosion-prediction models should not be uncritically applied to agroforestry situations; research specifically on the special conditions of trees and shrubs in erosion control is required. In the interim, however, there are strong indications that agroforestry design should focus on maximizing cover of the soil by plant residues during the period of erosive rains.

The importance of soil cover

Besides the conclusion obtained above on the basis of predictive models, there is experimental evidence that soil loss can be greatly reduced by maintenance of a good ground surface cover.

An experiment of great elegance was conceived many years ago, that of suspending fine wire gauze or mosquito netting a short distance above the soil surface. The netting breaks the impact of raindrops, which still reach the soil but as a fine spray. The soil is kept bare by weeding, and downslope runoff is allowed to continue unchecked. This artifice reduces erosion to about one hundredth of its value on unprotected bare soil (Hudson, 1981, pp. 216-17; Cunningham, 1963).

Evidence of the same kind comes from experimental work under agricultural conditions. Even a crop regarded as having a relatively high erosion risk, such as maize, substantially reduces erosion as compared with bare soil (e.g. Elwell and Stocking, 1976). A higher plant density and a better

5. The barrier approach: a terrace riser formed naturally by accumulation of soil on the upper side of a hedgerow of *Gliricidia septum.* Leyte, Philippines.

rate of growth give more cover and increased protection (Hudson, 1981, pp. 211-12). Erosion under cereals can be greatly reduced by intercropping with leguminous cover plants such as *Stylosanthes* or *Desmodium* (El-Swaify et al., 1988). The contrast in protective cover between well and poorly managed crops is clearly seen in tea; a crop with close spacing, good growth and correct pruning provides a canopy cover of close to 100%, whereas poorly managed tea often leads to severe erosion; soil loss has been found to fall to low values where the canopy exceeds 65% (Othieno, 1975; Othieno and Laycock, 1977). Mixed cropping provides better cover than monoculture (e.g. Aina et al., 1979).

In oil palm plantations, erosion is prevented when the palms are young by a dense cover crop, often *Pueraria* sp. The nearly closed canopy of mature palms, however, shades them out. Erosion can be checked by placing pruned palm fronds on the ground, optimally with tips downslope to create inward flow towards the stems (Quencez, 1986; Lim, in press).

A ground cover of mulch is very effective in controlling erosion. With straw or crop residue mulches of the order of 5 t/ha, soil losses become small, whilst amounts of 1 to 2 t/ha can still have substantial effects (e.g. Lal, 1976a, 1976b, 1977a, 1977b, 1984; Okigbo and Lai, 1977; Abujamin, 1985). In western Nigeria, maize was found to reduce erosion by more

6. The cover approach: prunings of *Gliricidia septum*, together with maize residues, Form a complete ground-surface mulch in a hedgerow-intercropping system. Maha Illuppallama, Sri Lanka.

7. Combined barrier and cover approaches: hedgerows of *Leucaena leucocephala* with the prunings spread across the cultivated alleys. ICRAF Field Station, Machakos, Kenya.

than was predicted from canopy cover; it seems likely that the additional factor was crop residues on the surface (Wilkinson, 1975).

Outside the tropics, the use of crop residues, a living vegetative cover and no-till have been found to be an effective way to control erosion in the south-eastern United States; a 50% 'ground cover after planting' gives a cover factor (C) of 0.1; an 80% cover gives a factor of 0.05 (Sojka et al., 1984).

A special case of mulching occurs under the minimum-tillage system. No-tillage alone, without barrier-type conservation works, reduces erosion to well within acceptable tolerance limits (Lal, 1977b, 1984, in press). A mulch cover does not need to be complete; a spatial cover of 60% or over can reduce erosion to a small fraction of its value without cover (Rose and Freebairn, 1985; Rose, 1988; Stocking, 1988).

A notable practical example of cover control of erosion is reported from a moist subhumid highland area in Tanzania. On an agricultural plot on a 20-25° slope, erosion was kept to well below 1 t/ha/yr by cover-based management, including mulching with weeds and crop residues (Lundgren, 1980).

The relative effects of tree canopy, undergrowth and litter were compared in a study of a 5-year-old *Acacia auriculiformis* plantation under a lowland humid climate in Java. These three elements were removed artificially, singly and in pairs. The tree canopy alone had relatively little effect and the added effect of undergrowth was small. Litter cover alone, however, reduced erosion by 95% as compared with bare soil. Conversely, in a natural forest, measured erosion remained at under 1 t/ha/yr when both trees and undergrowth were artificially removed but litter retained, yet rose to 26 t/ha/yr with undergrowth and litter removed and the tree canopy retained. The situation of litter only cannot of course be maintained under natural conditions; decaying litter must be renewed by supply of fresh material from the canopy, which thus plays a role (Wiersum, 1985).

This evidence suggests that agroforestry systems are likely to be more effective in erosion control through supply of litter to the ground surface than through the effects of the tree canopy. Some multipurpose trees are deliberately chosen with a moderately open canopy to reduce shading effects. In spatially mixed agroforestry practices, such as home gardens, the multilayered plant structure may provide quite a dense canopy, but this is likely to be matched by the ground cover. In zoned practices, such as hedgerow intercropping, the canopy is necessarily limited to the tree rows, and frequently reduced by regular pruning; but a litter cover is provided where the prunings are placed on adjacent cropped alleys.

Evidence and induction therefore suggest that for erosion control:

1. The greatest potential of agroforestry lies in its capacity to supply and maintain a ground cover.
2. The direct effects of the tree canopy in providing cover are less than those of ground litter.
3. A soil litter cover, maintained throughout the period of erosive rains, frequently reduces erosion to within acceptable levels, even without additional measures of the runoff-barrier type.

Thus the direct prevention of soil erosion is most effectively achieved by a cover of surface litter, consisting of crop residues, tree prunings or both. The role of the tree canopy is to provide a supply of leafy material, through direct litter fall or pruning, sufficient to maintain this surface cover. From the point of view solely of erosion control, it is desirable that the litter should decompose relatively slowly, but this may conflict with a requirement for early release of nutrients to the growing crop. A design compromise may be possible by having a tree stand of mixed fast- and slow-decaying species.

Land classification, land evaluation and the use of sloping lands

There are two main approaches to classifying land with respect to its potential for land use: land-capability classification and land evaluation. Both take into account the risk of soil erosion.

THE BARRIER APPROACH AND THE COVER APPROACH

The *barrier approach* to erosion control is to check runoff and soil removal by means of barriers. These may be earth structures (ditch-and-bank structures, terraces), grass strips or hedgerows. The *cover approach* to erosion control is to check raindrop impact and runoff through maintenance of a soil cover formed of living and dead plant material, including herbaceous plants, crop residues and tree litter and prunings. Techniques include intercropping with cover crops, mulching, minimum tillage and agroforestry.

Agroforestry can contribute to the barrier approach directly, through the use of hedgerows as partly permeable barriers, and indirectly, through the role of trees in stabilizing earth structures and making productive use of the land they occupy. Agroforestry can contribute to the cover approach through the use of tree litter and prunings, in combination with the living crop cover and crop residues.

Analysis of the causative factors of erosion indicates that the potential of the cover approach for reducing erosion is greater than that of the barrier approach. Therefore, in designing agroforestry systems for erosion control, maintenance of a soil cover throughout the period of erosive rains should be the primary objective.

Land-capability classification

Land-capability classification originated in the United States, and has since been adapted and widely applied to land-use planning in developing countries. Land is graded into a number of capability classes, usually I-VIII, on the basis of its inherent limitations of erosion, wetness, soil and climate. Capability classes I-IV are 'arable', that is, are assessed as suitable for rainfed arable use, class V is applied to special situations, such as wet valley floors, whilst classes VI-VIII are 'non-arable', and considered suitable for grazing, forestry or conservation (Klingebiel and Montgomery, 1961; Dent and Young, 1981, pp. 128-39; Shaxson et al., 1977, pp. 148-58).

Of the limitations which determine these capability classes, the 'e' or erosion hazard limitation is usually dominant in practice. This is an outcome of the fact that the system was primarily designed for soil conservation purposes. In the conversion tables through which the limitations are converted into capability classes, erosion hazard is assessed by combinations of slope angle with properties representing the soil's resistance to erosion. The arable classes, I-IV, are distinguished from each other on two grounds, choice of crops and need for conservation practices, but that of choice of crops is in turn partly dictated by whether crops with high erosion risk (low ground cover) can or cannot be grown. By far the most common reason why areas of land are assigned to the non-arable classes is that of slope angle and consequent erosion risk.

Most versions of this scheme reach non-arable classification on only moderate slopes. An adaptation specifically for 'hilly, marginal lands' (based on Taiwan and Jamaica) permits cultivation on slopes up to 25° provided soils are deep, but calls for bench terracing or other labour-intensive structures above 15° (Sheng, 1986, pp. 5-16).

The outcome of using land-capability classification as a basis for land-use planning is therefore that all moderately to steeply sloping land is mapped available only for non-arable uses. For many areas in developing countries, this result is in conflict with current land use, and to attempt to apply it would be completely unrealistic. Areas of sloping land are already being used to grow subsistence food crops, and families and sometimes whole communities are dependent upon this produce; large areas in Rwanda, Burundi, Ethiopia and Malawi are examples. It would be socially desirable and impracticable to attempt to change this situation. Ways must be found of permitting food-crop production to continue on sloping

In Asia, this problem has been commonly solved by terracing, as for example in North Yemen, Java, the Philippines and the Himalayan foothills India and Nepal. By this means, what would be capability class VI and VII land is put to arable use, rainfed or irrigated; provided that terracing is maintained, soil and water conservation are achieved (although fertility line may still present a problem). However, this solution requires a avarage amount of labour, spread over many years to build one extra terrace Year, and it is unlikely that it can be introduced to regions where it is already customary.

Land evaluation

The approach of land evaluation, areas of land are assessed with respect to their suitability for a number of defined uses, called land-utilization stages. Where applied at a reconnaissance scale, these can be major kinds , such as arable, pasture and forestry. For most planning purposes, However, the land utilization types are specified in more detail, e.g. 'arable conservation, rotation of maize with cowpea, no fertilizer, hand cultivation, Soil conservation works'. A land use identical except for the specification bunds' would constitute a different land-utilization type, for which Posessed suitabilities would differ.

Land suitability for a specified use is assessed by comparing the requirements of the use with the properties of land, the latter termed land qualities; examples are moisture availability, nutrient availability, and potential for mechanization. Thus if the land use has a given requirement, say sufficient moisture availability to give a growing period of 120 days, and an area of land possesses that length of growing period, then on the basis of moisture availability the land is rated suitable for that use.

In this approach, erosion hazard is treated as a land quality. The 'land-use requirement' is commonly taken as some rate of erosion which is considered acceptable, e.g. 10 t/ha/yr. Erosion under the specified use is estimated for each land unit, using one of the predictive models. Where the predicted erosion exceeds the acceptable level, that area of land is rated as not suitable for the use (FAO, 1983, pp. 113-20; Bennema and de Meester, 1981).

This method, with its emphasis on specifying land-utilization types in detail, provides a more flexible approach to land-use planning than that of land-capability classification. In particular, it permits the adaptation of a form of land use in such a way that it may become suitable on land to which it was originally unsuited; this process of successive adaptation between land and land use is known as matching (FAO 1976a, 1983, 1984; Dent and Young, 1981; Young, 1984a).

Agroforestry and the use of sloping lands

It is recognized that sloping lands, meaning areas dominated by moderate and steep slopes, form a distinct and widespread type of tropical environment with special problems, foremost among which is erosion (Novoa and Posner, 1981; Siderius, 1986). The introduction of agroforestry practices may provide a solution to the dilemma implied by the existence of a high erosion hazard under conventional arable farming on sloping land together with the fact that large areas of such land are already under arable use and must remain so. Certain practices, including barrier hedges, hedgerow intercropping and multistorey tree gardens, have the potential to permit arable cropping on sloping land coupled with adequate soil conservation, leading to sustained productive use. Current trials in Ntcheu District, Malawi, illustrate this situation. Owing to population pressure, cultivation in this area has been widely and irrevocably extended onto land with slopes of 25° and over. A system of closely spaced barrier hedges is being tried with the specific aim of finding a way of making maize production sustainable on land which would conventionally have been classified as non-arable.

It is neither desirable, nor practicable to introduce an additional class of land use, 'agroforestry', into land-capability classification (as was attempted by Sheng, 1986, pp. 55-60). The capacity of different agroforestry practices to achieve erosion control varies so widely that no limiting values of slope could be set for agroforestry as a whole. Capability classification is in any case becoming less widely favoured, and no useful purpose would be served by adapting it for agroforestry.

Land evaluation, on the other hand, is well adapted to the circumstances of the introduction of agroforestry practices into existing land-use systems. Any specific agroforestry practice, together with details such as tree and crop species and density, can be taken as a land utilization type, and its suitability on a number of given areas of land assessed. Details of the manner of assessment fall outside the scope of the present review, but the relevant point is that such assessment will include the potential for erosion control. By this means, it is possible to assess the suitabilities of existing land-use systems, and compare them with alternative forms of improved land use, both agroforestry and non-agroforestry. The design stage of agroforestry diagnosis and design is very compatible with the approach of matching in land evaluation (Young, 1984a, 1986b).

A question of great importance from the point of view of policy and investment is: 'in which areas are the potential benefits from agroforestry the greatest?' Since funds for research and development are limited, it is clearly desirable to know which areas should have priority. Much work still needs to be done on this question, but one feature relevant to the present discussion is clear: that among the areas regarded as having a high potential for agroforestry, sloping lands are notably common. This is illustrated by areas for which ICRAF has participated in collaborative or advisory projects. Out of the first eight areas in the original collaborative programme, two could be classified as moderately sloping and five contained much steeply sloping land. This experience is being continued, for example in recent cooperative work in Rwanda, Ethiopia, Nepal and Malawi. Whilst this is no evidence of a statistically provable nature, there can be no doubt that, of various broad sets of environmental conditions, that of sloping lands is one of the highest in its potential for agroforestry (Young, 1986c).

Erosion, soil productivity and economics

Erosion and soil productivity

Only in recent years has sufficient attention been directed towards the basic question of the effect of erosion on crop yields and soil productivity. Soil conservation was formerly justified on the more general grounds of preventing the complete loss of the natural resource of soil, thereby putting land out of production. This is a valid long-term view, but does not satisfy the equirements of economic analysis. To justify soil-conservation measures in economic terms, it is necessary to show that erosion reduces land productivity. Most of the earlier research on this subject was based on the United States, and it is only since 1980 that substantial attention has been directed towards erosion and productivity on tropical soils.

The significance of this question for agroforestry lies not in any specific technical potentialities of agroforestry, but in establishing the basic importance of soil conservation from a social and economic point of view. Aid and investment have to be justified on the grounds of maintaining food production and providing an economic return on investment. If research into agroforestry is to be justified on the grounds of its potential to control erosion, then the approximate consequences of unchecked erosion must be known. Hence a brief summary of the current state of knowledge is given here. This is based mainly on recent review papers as follows: Bennema and de Meester, 1981; Higgins and Kassam, 1981; Stocking and Pain, 1983; Stocking, 1984; Rijsberman and Wolman, 1984, 1985; ASAE, 1985; Crosson, 1985; Follett and Stewart, 1985; Lai, 1985; Larson et al., 1985; Stocking and Peake, 1985, 1986; Williams, 1985; Yost et al., 1985; Flach, 1986; Peake, 1986.

The first attempts to relate productivity to erosion were based on loss of soil depth. Assume that a soil is 1 m deep, that it becomes uncultivable when the depth falls below 20 cm, and that erosion is at the quite severe rate of 60 t/ha/yr, equivalent to 4 mm of soil thickness. Productivity will then be reduced to zero in 800/4 or 200 years. The simplest assumption made was that the decrease in productivity with depth was linear, so that in the example given, crop yields would fall by 1/200 or 0.5% per year. Not surprisingly, analysis based on such reasoning showed that investment in conservation could rarely be justified in economic terms, other than on initially shallow soils.

An advance was to estimate the effects of loss of topsoil not merely on depth but on other soil properties. In regions subject to drought or dry spells, reduction in depth is likely to lead to significant loss of the soil's water-holding capacity. A soil-productivity index was devised, based on the assumption that the major function of soil is to provide a medium for root growth. The productivity index, PI, is given by:

where A; is an index of available water capacity in soil layer i, Q similarly for bulk density, and D_t for pH. WF_i is a weighting factor for layer i, based on the proportion of roots present in each layer. In some tests of the model for tropical conditions, additional factors of organic carbon and gravel content were added. Steps in assessing the effects of erosion are:

1. Calibrate the factors A, C, D and any others used with respect to their effects on crop yield in the area under study; an ideal soil has factor values, and thus a PI index, of 1.0.
2. Determine the productivity index for each soil type in its present condition.
3. Assume layers of various thicknesses are removed from the soil surface

by erosion (without change to properties of the remaining layers), and recalculate the productivity index for each soil.

The results of applying this method to the continental United States showed greater effects than those derived from consideration of soil depth only, but these were still only moderate; the loss of 50 cm of soil produced a lowering of the productivity index by over 0.3 in only 16% of soil types covered. Tests were carried out in Hawaii, Nigeria. India and Mexico, although in all cases with problems of data shortage; results varied widely between soil types, a simulated loss of 20 cm of soil sometimes producing a productivity decline of 20-40%, but in other cases, no decrease at all (Rijsberman and Wolman, 1984, 1985: Larson et al.. 1985).

A more sophisticated model has recently been developed, the Erosion-Productivity Impact Calculator (EPIC). This is of considerable complexity. taking into consideration many variables of weather, hydrology and soil; in particular, it calculates the cycling of carbon, nitrogen and phosphorus. The model has been successful in predicting sediment yields, soil changes and crop yields in the USA, and it is to be hoped that it will be tested for tropical conditions (National Soil Erosion.... 1981; Williams et al., 1982; Williams. 1985).

In field studies, much early work was based on artificial desurfacing, the manual removal of a layer from the soil surface followed by growing of a crop on the soil that remained. A big step forward was made in the discovery that this method underestimated the reduction in crop yield by erosion. Comparison between soils with artificial desurfacing and plots subjected to high rates of natural erosion showed that for equivalent volumes of soil removed, yield decreases were far greater on the latter. In one instance, the yield decrease brought about by natural erosion was 16 times that caused by artificial removal of the same thickness of soil.

The reason lies at least partly in the fact that eroded sediment contains a substantially higher content of organic matter and nutrients than that of the topsoil from which it is derived. The difference is called the *enrichment factor* in eroded sediment; for example, if the topsoil has a nitrogen content of 0.02% and eroded sediment a content of 0.4%, the nitrogen enrichment factor is 2.0. Enrichment factors for carbon and the major nutrients are frequently in the range 2 to 4, and occasionally as high as 10, being higher on gentle slopes and for moderate as compared with rapid erosion (Roose, 1977a; Bhati, 1977: Lal. 1980: Stocking. 1986). Reasons may be. first, that the uppermost few millimetres of soil are richer in organic matter and nutrients than the 15 or 20 em normallv bulked for analysis, and. secondly, that erosion selectively removes nutrient-rich material; the relative importance of these factors is not known.

Although quantitative data from studies on tropical soils are still scarce, present findings are as follows:

1. Tropical soils tend to suffer several times higher rates of crop-yield

reduction than temperate soils on which there have been equivalent volumes of soil loss.

2. In both the tropics and the temperate zone, yield decline is most rapid at first, that is, for the initial 10-20 cm of soil loss, after which the rate of yield reduction decreases exponentially. On ferric lixisols, the first 10 mm (ca 140 t/ha) of erosion will cause a reduction in yield of the order of 75%; for further erosion, the reduction is slower.
3. Yield decline is greatest on 'old' soils, that is, highly weathered tropical soils, in which there is a high concentration of organic matter in the topsoil. Another way of expressing this is that relative yield loss is greater on soils that are initially of lower fertility.

These findings are all explicable if it is assumed that the major effect of erosion on crop yields is through loss of organic matter and associated nutrients, coupled with the nutrient enrichment effect. Tropical soils have a higher relative concentration of nutrients in the topsoil as compared with temperate soils, and this feature is greatest in the highly weathered soils of intrinsically low fertility. Once the relatively nutrient-rich topsoil is removed, further erosion of the same volume of soil will remove fewer nutrients.

A schematic calculation illustrates the orders of magnitude involved. As an example of a widespread soil type of low inherent fertility, consider a plateau sandveld soil (p. 6). Under natural vegetation, this is likely to contain about 0.1% of nitrogen in the top 15 cm. Assume a topsoil bulk density of 1.0, erosion at 10 t/ha/yr and a nitrogen-enrichment factor in the eroded sediment of 4.0. There will be a loss of 40 kg N/ha/yr, equivalent to *removing* two bags of fertilizer per hectare!

This effect has been confirmed experimentally in Zimbabwe, in a five-year experimental study of nutrient losses in runoff water and eroded sediment. Regressions between soil loss and nutrient losses showed that erosion of 30 t/ha/yr causes a loss of about 50 kg nitrogen and 5 kg phosphorus per hectare, considerably greater than the amounts actually applied in fertilizer. The financial cost of replacing eroded nutrients varies from US$20 to 50 per hectare on arable lands and from US$10 to 80 per hectare on grazing lands (Stocking, 1986, in press).

The apparent absence of yield decline on land in western countries believed to have suffered erosion may be because the addition of fertilizers can mask the effects. There is evidence of the same feature in the tropics; relative yield reduction is greater on unfertilized plots than on the same soil with added fertilizer (Yost et al., 1985). The 'solution' of counteracting the effects of erosion by adding fertilizer is, of course, not open to most farmers in less developed countries.

A second important influence on crop yields is that of soil physical conditions, made up of complex interacting properties, including structure, aggregate stability, porosity, bulk density, infiltration capacity and available water capacity. These properties are partly determined by the basic conditions of texture and iron minerals present, but are also substantially influenced by the variable factor of soil organic matter content. Lowering of organic matter normally leads to loss of porosity, decline in aggregate stability, increase in bulk density and lowering of infiltration capacity. These in turn cause substantial reduction in crop yield (cf. papers in Lai and Greenland, 1979).

The concentration of organic matter in topsoil, coupled with the carbon-enrichment ratio in eroded sediment, means that erosion can substantially lower soil organic matter. Taking as an example a soil with 2% carbon content in 15 cm of topsoil, erosion of 50 t soil/ha/yr with a carbon enrichment ratio of 2.0 will cause an annual loss of 2000 kg C/ha. Continued over five years, such erosion would reduce topsoil carbon by one third of its former value, leading to substantial degradation of physical properties.

Evidence of a different kind comes from a study of two sample areas in the Philippines in which farmers themselves were asked to assess the erosion problem on their land as 'very serious', 'less serious' or 'no erosion'. This was related to reported crop yields (Table 8). In all cases, yields were lower with very serious than with less serious erosion, 45-48% lower for the largest samples, the farmers reporting rice and maize yields.

The third cause of reduced yields is not from erosion itself but from the increased runoff and reduced infiltration with which it is associated. In humid regions this does not matter, since at the time of most rainfall the soil is at field capacity. In dry savanna and semi-arid regions, however, moisture stress is often the limiting factor upon crop yields. The increased infiltration brought about by conservation measures can substantially increase the periods during which the soil profile is at or close to field capacity, thus reducing moisture stress.

In the longer term, reduction in soil depth leads to lowering of available

Table 8. *Crop yields by degree of seriousness of erosion, as judged by farmers in the Philippines (Librero, 1985).*

	Very serious erosion	Less serious erosion	No erosion
Rough rice	484	715	659
Shelled maize	196	284	I03[a]
Bananas	544	1204	912
Cassava	176[b]	2387	4140
Coconut (nuts/ha)	270[b]	3858	4567
Coffee	81[b]	82	51[b]

[a]Explained by low planting densities.
[b]Bascd on sample of less than 5 farms.

water capacity. This not only reduces average crop yields but also increases the risk of crop failure through drought. This has been treated as the principal adverse effect of erosion in one analysis (Biot, 1986).

Erosion may adversely affect the growth and functioning of the trees themselves in agroforestry systems. In Hawaii, 'simulated erosion" (removal of 7.5-37.5 cm topsoil) greatly reduced nodulation, nitrogenase activity, nutrient uptake and growth of *Sesbania grandiflora* (Habte and El-Swaify, 1986).

Two conclusions emerge, the first relating to soil conservation in general, the second of specific relevance to agroforestry. First, recent work on the relations between erosion and productivity has confirmed and strengthened the view that loss of crop production through lowering of yields brought about by soil erosion is substantial. Given the fact that population pressure on land has led to more or less continuous arable cropping over wide areas, erosion is likely to be one cause of the low yields commonly occurring on such land.

Secondly, the main causes of yield reduction by erosion, in the short and medium terms, are lowering of fertility through loss of organic matter and associated nutrients, together with the effects of organic-matter loss on soil physical properties. In dry regions, loss of soil moisture by runoff is a further important factor. Hence the problem of erosion control, in the sense of controlling the mass of soil removed, is closely linked to the problem of maintenance of fertility. This is a central theme of the present review. Specifically, agroforestry practices in which erosion control is combined with improvement of fertility are likely to be of particular value, and the potential to combine these functions should be an aim in the design of agroforestry systems.

Economic analysis of soil conservation

Given the strong competition for the use of investment funds, whether these originate from external aid or internal government revenue, it is difficult to implement soil-conservation measures unless they can be justified in economic terms. The alternative means of justification is to appeal to conservation of natural resources as desirable in its own right, or for the use of future generations; whilst a valid point of view, this is likely to carry less weight in making decisions on allocation of development funds.

Cost-benefit analysis of soil conservation, whether on a private (farmer) or social (community) basis, is essentially a matter of comparing discounted net revenue with and without conservation measures. Both costs and benefits are likely to be affected. For a soil-conservation project of the conventional kind, such as bunds and waterways with mechanical construction, there will be a high initial capital cost, together with limited annual maintenance costs (zero if this is assumed to be done by farmer's labour in off-peak periods).

This must be set against the difference in benefits, represented as crop yields at farm-gate prices; the simplest assumption is a constant yield with soil conservation, to be compared with a declining yield without. Specification of the expected crop yields, for the number of years taken as the basis of economic analysis, is essential.

With the earlier approach to erosion-crop relations, based on soil depth, it was rarely possible to demonstrate acceptable benefit-cost ratios or internal rates of return, i.e. values comparable with the returns from investment in other forms of development. This remains true even at low rates of discounting. The decrease in yields on a soil-depth basis is too slow, or too far in the future, to have an appreciable effect on discounted benefits. Where this was the case, there were two ways of attempting to justify conservation: by treating it as a special case economically, taking a long project life (e.g. 100 years or more) and a zero rate of discounting, or by regarding conservation as a prerequisite of other agricultural improvements and not analysing it as a separate element.

This situation has been changed through recognition of the substantial crop-yield reductions brought about by nutrient losses through erosion. It has become possible to justify conservation projects in conventional economic terms (e.g. Dumsday and Flinn, 1977; Wiggins, 1981; Bojo, 1986). Instead of the eventual loss of production when soil depth is reduced below a minimum level, it is the rapid decline in yields in the initial years of unchecked erosion which is significant.

A more direct approach is to estimate the losses of nutrients by erosion and to calculate the cost of replacing these as fertilizer. For the arable lands of Zimbabwe, and considering nitrogen and phosphorus losses only, cost was estimated at $150 million a year (1984/85), which is three times the amount actually spent on fertilizers (Stocking, 1986, in press).

Even if justifiable in terms of yield losses or fertilizer-replacement costs, problems remain in implementing conservation through physical works. If constructed by earth-moving machinery, the sheer cost makes large demands on capital. Construction by hand labour is possible, but farmers are rarely willing to do so since there is no perceived return from the high labour input.

Another relevant aspect of economic analysis is that the costs of soil conservation increase in the order prevention < control < reclamation. Least costly is to prevent serious erosion commencing on land initially in good condition; to control and reduce erosion where it is already occurring requires greater inputs and investment; most expensive is to reclaim and rehabilitate severely degraded land.

On land already degraded, however, it may become possible to justify reclamation forestry in economic terms by combining it with production. After an initial period of soil improvement under forest, the tree cover can be thinned and grass beneath cut for sale as fodder; positive benefit :eost ratios have been achieved for such a practice in India (Mathur et al., 1979).

With respect to economic analysis of conservation, conclusions of particular relevance to agroforestry are:

1. The initial cost of establishing erosion-control works based on agroforestry, whether in terms of capital or labour, is frequently lower than that of terracing or bunds. The infrastructure costs of agroforestry, such as tree nurseries, are on a modest scale.
2. In addition to the benefit from maintenance of crop yields through control of soil loss, some agroforestry practices may have the potential to lead to an increase in crop yields, above present levels. In addition, there are benefits from the produce of the trees. Through either or both these effects, there can be an increase not only in actual benefits, but in those perceived by the farmer.
3. On land already degraded, the cost of reclamation can be reduced if soil-improving trees are combined with controlled production.

Conservation and extension policy

There has been a policy change in the way in which soil conservation is applied in the field: the earlier approach of compulsion has given place to one of persuasion and cooperation.

The earlier approach was based on passing laws or regulations governing land use, and enforcing these. Such 'agricultural rules', as they were called, commonly included:

- forbidding cultivation on slopes of more than a certain steepness;
- forbidding cultivation within a specified distance from a water course;
- requiring the construction of bunds or other conservation works before permission was granted for land to be taken into cultivation.

Enforcement was generally by warning or threat, backed by legal prosecutions in extreme cases.

In the tropics, this approach was mainly applied in the context of colonial government, and under conditions of relatively low pressure on land. Although now commonly derided, it achieved in its time a substantial measure of success in controlling erosion; an example is the complete coverage of large areas of Zimbabwe (then Southern Rhodesia) with well-designed and maintained systems of cut-off drains, bunds and waterways.

The policy of applying conservation by prohibitive or compulsory means is now not effective. There were always difficulties, particularly in that agricultural extension staff, whose job it was to help the farmer, did not wish to be associated with enforcement. In Africa, the policy was associated with colonial rule and thus became anathema to newly independent governments. Many of the rules are still on the statute books, but are no longer applied.

The present policy is to apply soil-conservation measures through persuading farmers that it is in their interests to do so, and securing their cooperation. This is not simply a matter of prevalent attitude of mind: it is, in fact, a more effective approach. Unless a land-use practice has the support of the farming community, it will never be applied. Where a few individuals act contrary to the interests of the majority, some measure of enforcement will still be necessary, but this itself must come from within the local community (Christy, 1971; Young, 1977; Blakie, 1985; Wilkinson, 1985; Roose, in press; Shaxson et al., 1989; Shaxson, in press; Hudson, in press).

Another trend in policy is away from soil conservation treated in isolation and towards its integration into farming systems as a whole. This is part of the growth of the farming-systems approach to development. Such systems of improved agriculture have been called 'conservation farming' or 'integrated land use'.

These points are summarized in a recent review of soil-conservation strategies, as follows (Stocking, 1985b):

- de-emphasize conservation as an isolated measure; it should be part of integrated methods of land-use improvement;
- use simple methods, within the capacity of farmers to establish and maintain;
- provide external support for sound traditional farming practices;
- train local extension services; this is vital and in many countries needs to be greatly improved;
- 'Conservation requires that the farmers respect and support the measures [which] must be evaluated for their overall impact on farming and on the livelihood of the people.'

These trends are highly compatible, both with the nature of agroforestry and with its development through the approach of diagnosis and design. It is a fundamental aim of agroforestry design that systems should combine productivity with sustainability; thus, there is an immediate real and perceived benefit, whilst at the same time conservation is achieved. Many agroforestry practices are relatively simple to implement, and it has almost invariably been the case that they are put into practice by the farmers themselves, whether as indigenous practices or through adoption of innovations.

The approach of diagnosis and design has the element of farmer acceptance and cooperation built into it. The farmers are consulted at the stage of diagnosis as to what is their perception of the problems of the system; these are very often likely to include low crop yields, although erosion may or may not be perceived as one of the causes.

Local constraints, e.g. of labour, capital or supplies, are established and taken into account in designing improved systems. Any proposed changes are put to the farmers for their opinions—when it may often be found that what the scientist considers to be 'improvements' are regarded locally in another light! The essential feature is that the former sequence in which technical design was followed by the problem of acceptance has been replaced in the diagnosis and design procedure by one in which acceptability is built into the system from the start. Since this approach is applied to the agroforestry system as a whole, it necessarily covers whatever elements of soil conservation it may include.

The system of 'conservation farming' in Sri Lanka includes three features of agroforestry (hedgerow intercropping, fuelwood trees and fodder trees) together with management of pests and diseases (in part by tree litter), mulching and minimum tillage. 'Integrated land use' as applied in Malawi places emphasis on planting trees along contour barrier strips and marker ridges (Weerakoon, 1983; Commonwealth Secretariat, 1983; Wijewardene and Waidyanatha, 1984; Douglas, 1988).

The experience of the Central Visayas Project, the Philippines, illustrates both the approach to conservation through active cooperation with farmers and the use of agroforestry as a conservation technique. The project has been successful in getting farmers to adopt conservation measures, a success attributed to the following factors (Queblatin, 1985):

- farmers are involved in defining their own problems and identifying solutions; they are made to understand the value of conservation for their own interests;
- the solutions adopted, such as *Leucaena* barrier hedges, are simple and can easily be implemented by farmers themselves; use is made of local resources, e.g. indigenous trees in areas of acid soils where *Leucaena* does not grow well;
- soil conservation is linked to other farming concerns; for example, using napier grass together with *Leucaena* in hedgerows where this is attractive to farmers raising livestock.

The fact that agroforestry combines erosion control with soil fertility maintenance and production makes it more acceptable to farmers than systems of erosion control by earth structures. At the same time, its techniques are relatively inexpensive, and lie within the capacity of small farmers to implement. These aspects of agroforestry render it highly appropriate in the light of recent trends in conservation policy.

Chapter 5
Experimental Evidence

Evidence of the role and potential of agroforestry for control of erosion is of two kinds. First, there are experimental studies based on land-use systems which include a tree cover, from which inferences may be derived on the likely effects of trees on the causative factors of erosion. Secondly, there are measurements of erosion rates under agroforestry systems, on farms or experimental stations; these are at present few in number. This chapter draws upon an excellent review by Wiersum (1984), which contains additional references.

Effects of a tree cover on the factors of erosion

Rainfall erosivity

Raindrop energy is not substantially reduced by a high tree canopy. Anyone who has walked through rain forest during a storm will be aware of this. Raindrops reach over 95% of their terminal velocity in a free-fall distance of 8 m, whilst drop size may be increased through accumulation on leaf surfaces and fall from their tips. High erosivities have been recorded under forestry plantations. In teak plantations, where the canopy is high and leaves are shed for part of the year, severe erosion has sometimes occurred. In an experimental study based on artificially removing the canopy of an *Acacia auriculiformis* plantation in Java, it was found that the presence of the canopy *increased* erosive power by 24% (Wiersum, 1985).

Under a mature oil palm plantation, despite a closed canopy, the large drops falling from frond tips have a high kinetic energy, causing substantial erosion (Lim, in press). In both a home garden and a bamboo plantation in Java, rainfall erosivity above the herbaceous and litter layer was 127-135% of that of incident rainfall, owing to large drops falling from leaf drip-tips (Soemarwoto. 1987).

A dense canopy of low trees or shrubs, such as is provided by coffee or tea bushes, reduces erosivity. although the shade trees in plantations increase it (Wiersum, 1984). In spatial-mixed agroforestry systems, therefore, any such effect will depend on the height of the canopy. In spatial-zoned systems, including hedgerow intercropping, the canopy is usually low but it is not vertically above the cropped land. Thus the tree canopy cannot be expected to reduce rainfall erosivity to any substantial degree. For erosion-control purposes alone, there is no purpose served in attempting to maximize canopy cover in agroforestry design.

Soil erodibility

It is widely observed that soil structure is of higher grade and more stable, with lower detachability and higher infiltration capacity, under forest than under cultivation. Under shifting cultivation, organic matter decreases and erodibility increases during the cropping period. Under taungya systems, there is usually a decrease in organic matter content and infiltration capacity, and higher erosion, during the cropping period, as compared with a forest plantation without taungya. Higher erodibility has been recorded for a home garden in Tanzania and a multistorey tree garden in Java, as compared with natural forest in the same areas (Lundgren, 1980; Wiersum, 1984).

The position is different if soils under arable use are taken as the basis for comparison. Most agroforestry systems are capable of maintaining soil organic matter at levels higher than under pure agriculture, and organic matter is the major variable factor controlling resistance to erosion.

In the nomograph employed in the universal soil loss equation, a rise of 1% in topsoil organic matter decreases the value of the K factor by 0.04, or possibly 0.05 if the independently rated effect on permeability is added. Thus an agroforestry system which maintained organic matter at 1.5%, compared with 1.0% under agriculture, might lower the K factor from, say, 0.350 to 0.325, leading to a lowering of only 7% in predicted erosion. Therefore the probable influence of agroforestry in improving the soil's resistance to erosion by maintaining organic matter, whilst in a favourable direction, is not large.

Redaction of runoff

Earth barriers, such as storm drains and the various forms of ditch-and-bund structures, completely check runoff unless they are overtopped and broken; the runoff either infiltrates or is channelled to waterways. By contrast, biological barriers, including grass strips and hedgerows, are partly permeable.

The very limited experimental evidence suggests, however, that hedge barriers do in fact greatly reduce runoff (see below). Research is needed into the relative effectiveness of barriers of different widths on storms of varying intensities. There are two favourable adjuncts of the use of hedgerows. First, no water is channelled away from the plot, a benefit in dry regions. Secondly, the permeability provides an automatic safety valve for the occasional storms of very high intensity, which destroy earth barriers but can pass through hedgerows without damage.

Protection by the ground surface cover

The importance of a ground surface cover, of living vegetation or mulch, has been stressed above. The C, or cover, factor can range from over 0.5 on cropped land with bare soil between plants to between 0.1 and 0.01 or lower where a ground surface cover is maintained during the period of erosive rains. In the classic experiment on an *Acacia mangium* plantation in Java, artificial removal of the surface litter increased erosion by about 20 times (Wiersum, 1984).

This implies that where the objective is erosion control, it is highly desirable to distribute tree litter or prunings over the ground surface. In spatial-mixed forms of agroforestry, such distribution is more or less automatic. In spatial-zoned systems, such as hedgerow intercropping, there is a management choice between stacking the litter against the upper side of the hedge barriers or distributing it over the alleys. There are strong indications that both tree prunings and crop residues should be distributed over the ground surface, and neither stacked in lines nor incorporated into the soil.

A further implication is that tree species with a moderate to slow rate of leaf-litter decay are to be preferred. This may conflict with requirements for timing of nutrient release, for which rapid decay is often preferable. This dilemma might be resolved by hedgerows of two species, one with rapid and one with slower leaf decay.

Summary

For purposes of agroforestry design where erosion control is an objective, indications from indirect evidence, coupled with very limited experimental data, are:

1. The tree canopy is not likely to reduce erosion, and may actually increase it.
2. The potential of many agroforestry systems to maintain or improve soil organic matter will help to check erosion, but cannot be expected greatly to reduce it where conditions of climate, slope and soil cover are adverse.
3. Barrier hedges substantially reduce runoff and increase infiltration, whilst their permeability prevents destruction during occasional storms of high intensity.
4. Maintenance of a ground surface cover of 60% or more, formed by any combination of living herbaceous plants with plant litter, has a high potential to reduce erosion, and should be the primary objective in agroforestry design.

Experimental data for agroforestry

It is clearly desirable that statements about the effectiveness of agroforestry in controlling erosion should rest on a foundation of experimental measurements of erosion rates under actual agroforestry systems. These should include both data from experiment stations, under controlled conditions and replicated, and data from on-farm measurements. Results from work of this kind will greatly strengthen, and in part replace, the largely inferential treatment used in the present review.

A substantial amount of such data will soon become available. Erosion plots based on, or which include, agroforestry treatments arc currently being established in many parts of the world. Given that it may take two years to establish the tree and shrub component, one year to run the plot in, three years to obtain moderately reliable data and one year to publish, we can expect useful results of such measurements to appear in quantity by about 1993 to 1995.

A variable records

A summary of erosion rates under tropical forest, tree crops and some agroforestry systems is given in Table 9 (a summary of data drawn partly from unpublished or inaccessible sources). If the rates shown are classed as Low = <2 t/ha/yr, Moderate = 2-10 t/ha/yr, and High = >10 t/ha/yr, the results may be summarized 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
	Cropping period in taungya
High:	Tree plantation crops, clean weeded
	Forest plantations, litter removed or burned.

Table9. *Rates of erosion in tropical forest and tree crop systems (Wiersum, 1984).*

Land-use system	Erosion (t/ha/yr) 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 plantations, 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, burned or litter removed	5.92	53.40	104.80

A feature of the data is that in the systems which potentially have high erosion, the range of values is large, indicating the importance of management rather than the intrinsic nature of the practices. Also notable are the high rates under the last two systems shown, in which there is no ground surface cover of litter.

For *hedgerow intercropping,* erosion has been measured at Ibadan, Nigeria, on a 7% (4°) slope (moist subhumid climate, lixisol). Hedgerows of *Leucaena* and *Gliricidia sepium* at 2 and 4 m spacing were compared with no-till and conventional ploughing without hedgerows. Mean rates of soil loss over two years (t/ha/yr) were 8.75 under ploughing, 0.95 under hedgerow intercropping (mean of two hedge species, two spacings) and 0.02 under no-till (Figure 1). Reduction of runoff and nutrient losses followed the same pattern. Thus although hedgerow intercropping was not as effective as no-till, it reduced soil and nutrient losses, and runoff, to well below acceptable limits. These data are for a relatively gentle slope (Lai, in press).

On steep slopes in Colombia (humid climate, rainfall 4000 mm, one-year record), soil losses of 23-38 t/ha/yr under maize were reduced to 13 t/ha/yr

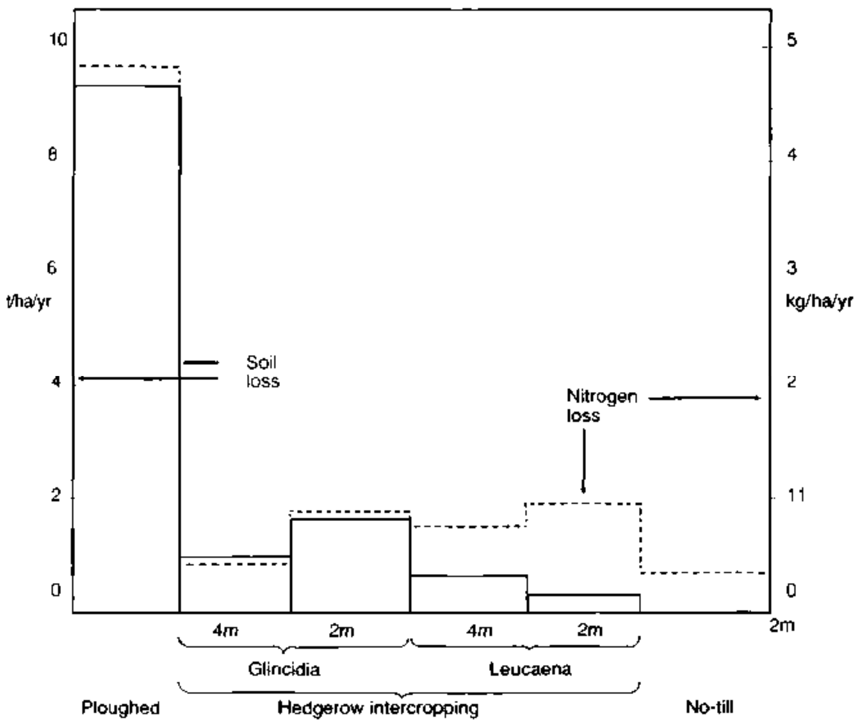


Figure 1. Losses of soil and nitrogen through erosion over two years under hedgerow intercropping, Ibadan, Nigeria (after data in Lal, in press).

(on both 45 and 75% slopes) by hedgerows of *Gliricidia septum* (van Eijk-Bos and Moreno, 1986).

A study on a 22° slope at Jalisco, Mexico (dry subhumid climate) offers striking evidence for the greater efficiency of soil cover than runoff barriers. Of seven plot treatments, that of maize with a surface mulch of litter cut from adjacent forest was by far the most effective, reducing erosion to 5.8 t/ha/yr, less than 10% of that under maize alone. There were similar reductions in losses of all major nutrients. Grass strips were much less effective in controlling erosion than forest litter mulch (Maass et al., 1988).

For *trees on conservation structures,* there are data for a 54% slope in northern Thailand (humid climate, rainfall 1700 mm. one-year record). Four plots were established consisting of drainage ditches along which were planted trees, coffee and lemon grass, with maize, rice and groundnuts cropped between. These were compared with a plot under traditional rice cultivation. Soil loss (t/ha/yr) was 52 under traditional rice compared with 13 (rice), 8 (maize) and 6 (groundnuts) for the conservation plots; rice yield was slightly higher on the latter (Hurni and Nuntapong, 1983).

Under *home gardens* in Java (humid climate), measured erosion was reported as 'minimal'. This was entirely due to the herbaceous layer and litter cover, since the canopy increased rainfall erosivity (Soemarwoto, 1987).

Data from the Usambara Mountains, Tanzania, (highland subhumid climate) refer not to agroforestry as such but to an unusually managed agricultural site (Lundgren, 1980). The farmer took all possible steps to maintain a ground cover: weeds were allowed to grow then cut and left as mulch, maize residues left, and mulch never burnt. Runoff was reduced to negligible amounts, lower than under natural forest, whilst soil loss was recorded as only 0.01 t/ha/yr on both 10-15° and 20-25° slopes.

There are no records of erosion under improved tree fallow. However, there is abundant evidence that during the cultivation phase of shifting cultivation, erosion rapidly increases, and there is no reason to suppose that the position would differ basically.

Summary

Experimental data for rates of erosion and nutrient loss under agroforestry practices, both under experimental conditions and on farm, arc at present very scanty. None of the available records, however, are contrary to the hypothesis that well-managed spatial agroforestry systems, both mixed and zoned, have the potential to reduce erosion to below levels that are acceptable, both as regards soil retention and prevention of loss in fertility. Substantially more records are expected by the mid 1990s.

Chapter 6
Agroforestry Practices for Erosion Control

The previous chapter has shown that direct experimental data on the effectiveness of agroforestry in controlling erosion is at present scanty, although increasing. Many countries, however, have begun to adopt agroforestry practices in erosion control, on a trial, demonstration or extension basis. In some cases these attempts are not based on controlled experimental data, whilst in others there may be unpublished local station records. In many small-scale demonstrations, there is no monitoring of erosion rates. However, observations on the apparent success of these developments, even if only qualitative, gives an indication of the range of practices available.

There is a distinction between supplementary and direct use of trees and shrubs in erosion control. In *supplementary use,* the trees and shrubs are not the primary means of checking runoff and erosion, but fulfil the functions of stabilizing conservation structures and making productive use of the land which these occupy. This applies mainly to the practice here called 'trees on erosion-control structures'. In *direct use,* the trees, shrubs or hedgerows are in themselves a major method of reducing erosion. This applies particularly to the practices of plantation crop combinations, multistorey tree gardens, hedgerow intercropping, windbreaks and shelterbelts, and reclamation forestry with multiple use.

The box on p.60 is arranged according to the classification of practices in Table 4 (p. 12). Practices with only slight effects on erosion control are excluded: trees on cropland and biomass transfer. Examples are illustrated in Figures 2 and 3 and Plates 8-14.

Rotational practices

Shifting cultivation

In the large literature on shifting cultivation there are many reports of the rapid increase in erosion rates after the first or second year of cultivation on steep slopes in the humid tropics (e.g. Kellman, 1969; Toky and Ramakrishnan, 1981). As is the case for soil fertility maintenance, erosion rates are acceptable under this system only when a short period of cultivation is followed by a long forest fallow. Where population pressure forces a

FUNCTIONS OF TREES AND SHRUBS IN EROSION CONTROL

Direct use:
- to increase soil cover, by litter and prunings
- to provide partly permeable hedgerow barriers
- to lead to the progressive development of terraces, through soil accumulation upslope of hedgerows
- to increase soil resistance to erosion, by maintenance of organic matter.

Supplementary use:
- to stabilize earth structures by root systems
- to make productive use of the land occupied by conservation works.

substantial increase in the ratio of cropping to fallow, severe soil degradation commonly results.

The forms of shifting cultivation found on savannas in the subhumid tropics are mostly practised on gentle slopes. Whilst there are severe problems of fertility, erosion is not commonly observed or reported as a contributory factor.

Improved tree fallow

Improved tree fallow is intended to simulate the effects of shifting cultivation but with the tree fallow consisting of planted species, selected for their soil-enrichment capacity or useful products. It has been reported on steep slopes in Cebu, the Philippines (Eslava, 1984). It may be expected to interact similarly to shifting cultivation: good erosion control during the fallow but with the danger of substantial erosion, and associated loss of carbon and nutrients, during the period of cropping. The practice would become more acceptable in systems in which a mulch cover was maintained by some means during the cropping period.

Taungya

Such limited evidence as exists on taungya systems suggests that there is indeed more erosion during the initial cropping period than would occur under a pure forest plantation. However, neither the loss of fertility nor effects on subsequent tree growth have been shown to be serious.

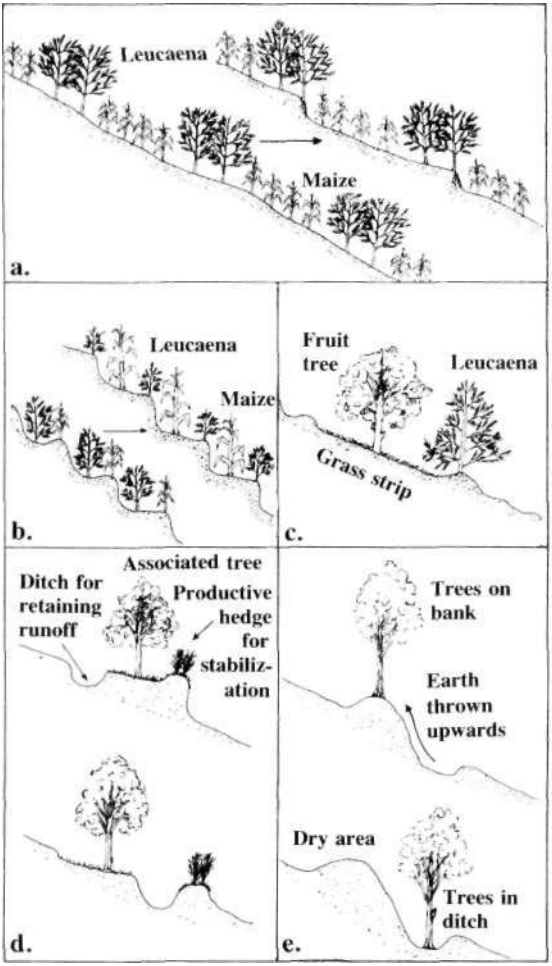


Figure 2. Examples of agroforestry in erosion control (1).

a. Barrier hedges of double rows of *Leucaena* with maize developing naturally into terraces, Philippines (after Cclcstino, 1985; Paeardo, 1985).

b. *Leucaena* barrier hedges planted at 90-cm spacing in furrows between rows of maize developing into terracettes, Malawi.

c. Trees on conservation works, Malawi: fruit trees on grass strips and *Leucaena* on marker ridges (ridges laid out along contours to guide cultivation ridges below).

d. Alternative arrangements for trees on conservation structures, Cameroon (after Simon. 1983).

e. Alternative positions for trees on *fanya juu* structures, Kenya. *Fanya juu* (literally 'throw (earth) upwards') structures are bunds in which the bank is above the ditch, promoting natural terrace formation (after Wenner, 1980; and at 1CRAF Machakos field station).

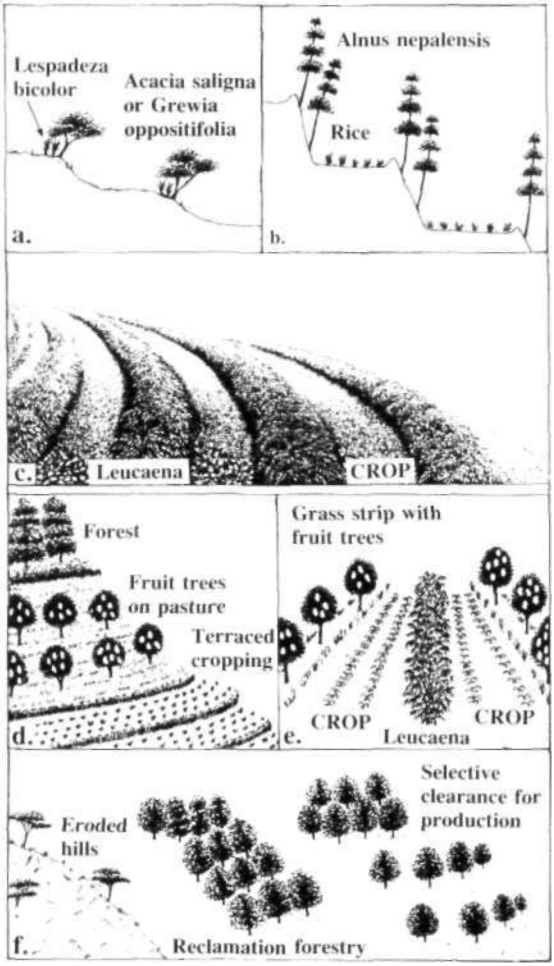


Figure 3. Examples of agroforestry in erosion control (2).

a. Trees on terrace risers, Ethiopia (after a recommendation for trials in von Carlowitz, 1986c).

b. Trees on risers of irrigated terraces, Nepal.

c. Hedgerow intercropping with *Leucaena* laid out on a slope (after a photograph in Kang et at., 1984).

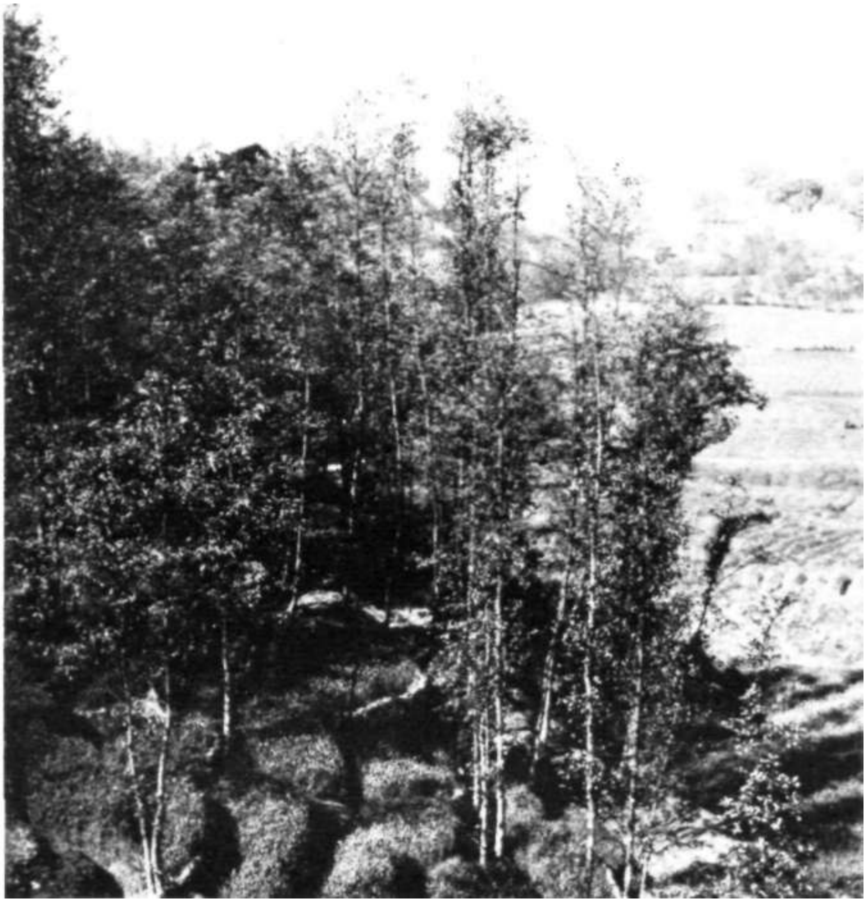
d. Model for land use as an alternative to shifting cultivation, north-east hills region, India (after Borthakur et al., 1979).

e. Plan view of suggested land use on slopes, combining barrier hedges with trees on grass barrier strips, Philippines (after Celestino. 1985).

f. Possible development of reclamation forestry into productive use by selective clearance of contour strips (based on Poulsen. 1984; Young. 1985b).

8. Supplementary use of trees in erosion control: fruit trees, here bananas, on grass strips. Maha lllуppallama, Sri Lanka.

1. Supplementary use of trees in erosion control: *Grevillea robusta* on the bank of a ditch-and-bank structure. Butare, Rwanda.



10. Supplementary use of trees in erosion control: *Alnus nepalensis* on banks of terraces irrigated for rice; the tall, narrow form is the result of repeated pruning. Kathmandu, Nepal.

Spatial-mixed practices

Plantation crop combinations

Large areas of the humid tropics are characterized by moderate to steep slopes and agricultural plantation crops, such as tea, coffee, cacao, oil palm, rubber and pineapple, are frequently grown on these areas. There have been cases of severe erosion, for example, under pineapple in Malaysia and on some tea plantations in Sri Lanka.

11. Contour hedgerows of *Leucaena leucocephala* on a hill-farming demonstration site. Leyte, Philippines.

12. Closely spaced contour hedgerows of *Leucaena leucocephala.* Ntcheu, Malawi.

13. A closer view of the site at Ntcheu, Malawi, showing micro-terraces formed naturally by each hedge.

A wide range of agroforestry systems fall under the practice of plantation crop combinations, having in common that an agricultural tree crop is grown in combination with other plants, which may be taller trees above it (as in systems of shade trees over tea, coffee or cacao), another tree crop (as in coconut with cacao, or coffee with bananas) or a herbaceous

14. A contour hedgerow consisting of four lines of *Leucaena leucocephala.* Hyderabad, India.

crop. The component plants may be spaced either randomly, as is common in indigenous systems, or regularly, as on plantations.

Where the shade trees are widely spaced, as is common in tea plantations and some coffee systems, their effect is not substantial, and erosion control depends on good management of the plantation crop itself. In some cases, however, both the upper and lower strata may be dense, as in the systems of coffee or cacao with *Cordia, Erythrlna* or *Inga* in Latin America, many of which occupy sloping land. Experimental studies of these systems are directed at nutrient cycling, but the fact that they may not attempt to measure erosion, coupled with the high element of nutrient recycling reported, is a clear indication that erosion is not a problem. It is most probably not the canopy that is responsible, but the capacity of these dense, mixed agroforestry systems to maintain a surface litter cover (for references, see Table 29, p. 176).

Even quite dense tree canopies of agricultural tree crops are not effective in erosion control unless there is a ground cover (Lim, in press). The management practice of keeping the ground bare through chemical weed control, for ease of maintenance, is highly undesirable from an erosion-control point of view.

Multistorey tree gardens

In multistorey tree gardens, a wide variety of woody and herbaceous crops are grown together in a dense pattern, at first sight disorderly but probably controlled by detailed management. Home gardens, consisting of plots of less than half a hectare around homesteads, are the most widely known, for example in Sri Lanka, Kerala (India), Java and Vietnam (Fernandes and Nair, 1986; Nair and Sreedharen, 1986; Mergen, 1987). Larger plots of similar multistorey structure are also found, such as the forest gardens of Sumatra (Michon et al., 1986).

Given the dense litter production all the year round, erosion control is inherent in such systems, confirmed by the fact that these systems clearly maintain fertility. The few measurements made suggest higher rainfall erosivity beneath trees than in the open, but considerably reduced erosion owing to the cover of herbaceous plants and litter (Soemwarto, 1987).

Spatial-zoned practices

Hedgerow intercropping and barrier hedges

Hedgerow intercropping (also called alley cropping) has multiple objectives, including fertility maintenance, and may be practised on flat or sloping land. Sometimes the tree component is made up of single or multiple rows of trees, but more often it consists of a dense hedgerow. Most experimental work has been conducted on level land, but the practice can be adapted to sloping land by planting the hedgerows along the contour.

Barrier hedges is the name given to contour-aligned hedgerows established specifically for erosion control on slopes. These have also been called biological bunds.

There is no clear distinction between the systems covered by these two names: hedgerow intercropping on slopes consists of barrier hedges, whilst a set of barrier hedges resembles a hedgerow-intercropping system. The same woody species are commonly used, and their erosion-control functions are identical. Whilst some may prefer to continue to employ the term barrier hedges for systems with the primary objective of erosion control, the two terms are here treated as interchangeable.

Functions. In systems of hedgerow intercropping on slopes, the functions of the hedges in soil conservation are:

- to check soil loss through the cover effect, by laying prunings on the ground surface in the cropped alleys;
- to reduce runoff, increase infiltration and reduce soil loss through the barrier effect;
- to maintain or improve soil fertility through the decay of prunings and root residues;
- to develop terraces progressively, through accumulation of soil upslope of hedgerows and stabilization of the risers by stems and roots.

Design. Variables to be taken into account in the design of such systems are hedge species, within-row plant spacing, width of hedgerows, spacing between hedgerows (or width of cropped alleys), and management of prunings. These aspects must then be reconciled with design considerations arising from purposes other than erosion control: production (e.g. fodder), soil-fertility maintenance, above-ground form (tendency to spreading), rooting pattern, and effects on pests and diseases.

As a hedge species, *Leucaena* has been the most widely used to date, but it is not ideal in erosion control as the leaves decay in one to two weeks, reducing soil cover. It has a demonstrated capacity to produce a dense hedge with high biomass production in climates ranging from humid to dry subhumid. For the purpose of ground-cover maintenance during the period of erosive rains, species with slower leaf decay such as *Cassia sianiea* or *Gliricidia sepium* are to be preferred. Combinations of species with differing rates of leaf decay should be tried.

The within-row plant spacing in hedgerows should be close. In humid and moist subhumid climates, direct sowing of seed has been successful, following which, seedlings can be thinned to a spacing of the order of 10 cm. Where seedlings are planted, as is necessary in drier climates, a 25 cm spacing appears to be sufficiently close: the gaps between stems are filled by crop residues and prunings coming to rest against the upper side of the rows. For two or more rows, the within-row spacing can be increased to 50 cm.

Hedges consisting of from one to four rows of plants have been tried, with single rows the most common. A single row minimizes loss of cropland, and can occupy only 0.5 m width if pruned low. Double rows, with the woody parts of prunings laid along the centre, form a more substantial barrier with less chance of gaps occurring. Hedgerow widths of over 10 m have been suggested for semi-arid climates, but evidence of the need for this is not given (Weber and Stoney, 1986, p. 147). Multiple-row hedges would be necessary if heavy storms damaged single rows by washing away whole plants, but this has not been observed. They would also be desirable if found to be substantially more effective in checking runoff or filtering out sediment; research is needed into whether this is the case. Another option is to plant a row of grass immediately above the hedgerow.

Guidance for the spacing of hedgerows comes at present only from the various formulae for vertical intervals between earth bunds or ditches found in national soil-conservation handbooks and textbooks; examples, with graphical solutions, are given in Hudson (1981, pp. 142-3). To what extent such formulae require modification for application to partly permeable hedgerow barriers is not known. For planting barrier hedges, what is needed is the inter-row distance along the ground surface. A highly approximate guideline is W = S/100, where W = inter-row spacing in metres and S = slope angle in degrees. Thus, hedges would be 5 m apart on 20° (36%) slopes. This should be modified for soil erodibility.

The grading, or gentle lateral slope, employed in some bund-and-ditch systems is not necessary with hedgerows, which can be laid out exactly along the contours. With such alignment, the between-row spacing will vary laterally.

A distinctive method is the use of narrow, verv closely spaced hedges on steep slopes. In Malawi, the standard width between rows of maize. 90 cm. has been retained, and *Leucaena* hedges planted between each row. Within a few years this produces micro-terracing. Whether the apparent strong root competition will lead to problems is not known.

There are two alternatives for management of primings: to lay them against the upslope side of the hedgerows, or to distribute them across the alleys. Laying prunings along the hedges immediately upon pruning serves to consolidate them as barriers and leave the alleys clear for tillage operations. Distributing prunings across the alleys is to be preferred both for erosion control, in providing ground cover, and for the soil-fertility effect of litter decay. For maximum cover, both woody stems and leaves should be distributed intact, which may necessitate hand planting of the crop.

Examples. In Flores Island, Indonesia (humid climate) over 10 000 ha of steep volcanic slopes have been stabilized since 1973 by contour hedgerows of *Leucaena;* progressive development of terraces is reported (Metzner, 1976; Prussner, 1981; Parera, 1983). Double rows of *Leucaena* have been used in conservation projects in the Philippines, in some cases alternating with grass strips with supplementary trees; there has been notable success in obtaining farmers' cooperation (Benge, 1979; Celestino, 1984, 1985; O' Sullivan, 1985). Hedgerow intercropping with mulching has recently been recommended as a means of tackling the severe erosion problems in Haiti (Zimmerman, 1986).

In Rwanda and Burundi, there are demonstration plots of hedgerow intercropping, on moderate to steep slopes, in a number of aid projects. At the Nyabisindu Project, Rwanda, both offset double rows and dense, randomly spaced hedgerows have been employed (Neumann, 1983; Michon and Bizimana, 1984; GTZ (Gesellschaft fur technische Zusammenarbeit), 1983; Anger et al., 1985; Lipman, 1986, pp. 130-31). Hedges at 4-8 m spacing have been employed in Cameroon (Simon, 1983). The distinctive, narrowly spaced hedges on steep slopes in Ntcheu District, Malawi, have been noted above; the demonstration plot is beside the main north-south road in the country. Large reductions in soil loss, as compared with a control plot under maize only, are reported (personal observation).

In the Philippines, single or double hedgerows of *Gliricidia* or *Leucaena* are being advocated as a technology for cultivation on sloping lands. In some examples, terrace fronts up to 1 m high have built up against them. Adoption by farmers has been variable.

At the ICRAF Machakos Field Station, Kenya (dry subhumid, transitional to semi-arid, bimodal climate), a barrier hedges demonstration plot was established in 1984, on an 8-10° (14-17%) slope. Hedges are single rows of *Leucaena*, 25 cm between plants, with rows 4 m apart. Both methods of pruning management are being tried. The hedgerows have become well established, and have led to incipient terrace fronts 10-20 cm high. Two crops a year (maize, legume) have been grown, with no clear indications of yield reduction through erosion. In 1988, this demonstration was converted into a set of erosion measurement plots.

Summary. Despite the paucity of experimental data, there are strong indications that systems of barrier hedges, or contour-aligned hedgerow intercropping, can provide an acceptable means of controlling erosion on gentle to moderate slopes, up to 17° (30%). This benefit is additional to the probable effects on soil fertility, reviewed below. It may also be possible to develop systems which permit cultivation of steep slopes on an environmentally sustainable basis, although this is more speculative.

The establishment costs of such systems are considerably less than for conventional earthwork-based conservation structures. Whether the labour required for regular pruning exceeds that for maintenance of earth structures will vary with circumstances.

The apparent high potential of this practice, and its applicability to sloping lands over a wide range of climatic conditions, justifies considerable immediate research. Where local trials and pilot demonstrations have been successful, more extended on-farm trials, possibly leading to general extension recommendations, may become justified.

Boundary planting and live fences

Field boundaries, where aligned along the contour, arc an effective means of erosion control. It is all to the good if this can be combined with productive and service functions through boundary planting or live fences.

Trees on erosion-control structures

Tree planting on erosion-control structures consists of the supplementary use of woody perennials as an adjunct to control of runoff and erosion achieved primarily by other means. The trees and shrubs serve, first, to stabilize earth structures through their root systems and, second, to make productive use of the land, e.g. for fruit, fodder or fuelwood. There is a further outcome—since trees are a relatively long-term feature, their presence on soil-conservation structures will tend to make these an integral and permanent part of the farming system. Trees and shrubs can be added where conservation structures are already in existence, or included when they are established.

There is less need for research into this practice, since its effectiveness for runoff and erosion control is largely that of the conventional conservation measures. A higher priority is the imaginative selection of trees that will meet farmers' needs.

There are three sub-practices: trees on grass barrier strips, trees on ditch-and-bank structures, and trees on terraces.

Trees on grass barrier strips. Where grass barrier strips have been found to be an effective and acceptable means of erosion control, the planting of trees on them can give added benefits of fuelwood. fodder or fruit production, according to the farmers" choice. This can be additional to fodder obtained from cut-and-carry grass. The strips are typically 2 m wide. Where the canopy is dense, as is the case for many fruit trees, the spacing should be moderately wide, e.g. 10 m, to avoid reduction in grass density.

The main design precaution is to avoid the use of trees which cause reduction in density of the grass sward. In management, it is important to protect the young trees by hoeing a bare earth circle around them for two to three years; otherwise grass competition can greatly reduce the rate of tree growth, particularly in dry climates.

Fxamples have been reported from the Philippines, Cameroon, Rwanda, Kenya and Malawi. Species used include *Grevillea robusta* for timber, and quinine, coffee, banana, guava, avocado, citrus and other fruit trees. Tree products can be combined with fodder from the grass.

Because of the land occupied by the strips, this practice is only suitable on gentle slopes. It appears to be best suited to subhumid climates.

Trees on ditch-and-bank structures. Many of the earth structures employed in erosion control consist of some combination of a ditch with an earth bank or bund. In the most common method, the ditch has a broad, shallow form and is upslope of the bank. An alternative known in Kenya as *'fanya juu'* ('throw (earth) upwards") has a narrower, steep-sided ditch with the bank upslope of it, with the objective of leading to progressive terrace formation (Wenner, 1980, 1981). Storm drains at the upper limit of cultivation are another component.

Such structures are conventionally stabilized by grass, but lend themselves to the planting of trees or hedges. *Grevillea robusta* is widely grown for timber in this way, but a wide range of multipurpose species can be planted.

The trees are usually planted on the banks, but in dry areas they can also be planted in the ditches. In the dry subhumid conditions (700 mm rainfall) of the ICRAF Machakos Field Station, six kinds of fruit tree planted in the ditches of *fanya juu* structures have shown good survival and growth, explicable by the fact that this is effectively a form of sunken planting, which has independently been found advantageous in this environment. Provided that the standard agroforestry precaution of avoiding trees incompatible with adjacent crops is followed, this practice can be safely recommended as a beneficial adjunct to standard soil-conservation works.

Trees on terraces. In sloping lands that are already terraced, there can be benefits from planting a dense tree cover on terrace risers. The trees are either pruned or coppiced. Functions are:

- stabilization of terrace risers, reducing the need for maintenance;
- production, of fuelwood, fodder or fruit;
- fertility improvement, by adding litter to the terrace treads.

Species can be varied according to climate and local needs. In India and Nepal, *Grewia oppositifolia* and *Abuts nepalensis* are widely used (Das, 1980; Fonzen and Oberholzer, 1984). In a consultancy report on the Gojam region of highland Ethiopia, planting of *Acacia saligna* and *Grewia oppositifolia* on risers of existing terraces was recommended (von Carlowitz, 1986c).'

The practice appears to be suited to many areas in which terracing is an established practice. This may be on land of moderate slope, but the practice has particular potential for the situation in which most of the available land consists of deeply dissected, steeply sloping valley sides, which have already been converted into terraces (rainfed or irrigated). Since population pressure is intrinsically high in such areas, they frequently have problems of fuelwood shortage, fodder shortage, declining soil fertility or all three. Erosion control is effectively achieved by the existing practice, so long as the terraces are maintained. There appears to be considerable potential for adding tree products, fertility improvement or both to this type of system by planting trees, thereby retaining soil conservation whilst enhancing production.

Where complete terracing is impracticable, productive multiple use of steep slopes is possible by planting/ fruit *trees on platform terraces*, individual semi-circular benches for each tree. For good establishment, a hole should first be dug and then partly refilled, to give sunken planting coupled with a loosened rooting zone. When the trees are mature, this can be combined with controlled grazing.

Windbreaks and shelterbelts

The role of windbreaks and shelterbelts in controlling wind erosion in semi-arid regions is well established. They are noted in passing here as an agroforestry practice of much importance, but are excluded from this review. Reference may be made to FAO (1976b, 1986), Jensen (1983) and Depommier (1985).

Sylvopastoral practices

Soil erosion on pastures is often more severe than on croplands. Severe sheet erosion and gullying are both common. The initial cause is degradation of the vegetation through overgrazing, which leads to a sparse, sometimes almost zero, ground cover, leaving the soil open to erosion. It is not uncommon for 10 cm or more of topsoil to be removed. Such erosion occurs both in semi-arid regions dependent primarily on grazing, and on land used for pasture in areas of mixed farming.

Sylvopastoral practices include scattered trees on pastures (e.g. systems with *Acacia albida* or other *Acacia* species), combinations of plantation crops with pastures (e.g. cattle under coconuts, sheep under rubber), live fences, fodder banks, windbreaks and shelterbelts, and hedgerow intercropping on pastures. The potential of windbreaks to control wind erosion is well established. It would be of great value if means were found for applying sylvopastoral practices to the control of water erosion.

If this is attempted simply by planting trees, without other changes in the management of degraded pastures, it will not be successful. The basic tenets of pasture management, such as restriction of livestock numbers and rotational grazing, are a prerequisite to erosion control as to any other aspect of sylvopastoral systems.

Given sound pasture management, however, trees may contribute to erosion control in a number of ways. It may be possible to use live fences to control livestock movement, assisting rotational grazing. The direct effect of the tree canopy in reducing raindrop impact is unlikely to be substantial.

However, the greatest potential is through indirect means. A known function of trees in sylvopastoral systems is to supply protein-rich fodder at times of year when grass is absent or indigestible. This can be through direct browse, as by sheep, goats and game animals, or through cut-and-carry fodder. By reducing grazing pressure, such methods can lead to a better vegetation cover and thus less erosion at the critical period, the start of the rains.

As with sylvopastoral practices in general, these considerations apply to semi-arid and subhumid grazing land, and to areas of the humid tropics where sloping land is used for grazing, as is common in Latin America. A wide perspective on the potential of sylvopastoralism in the semi-arid zone is given by Baumer (1987).

Reclamation forestry with multiple use

The potential of reclamation forestry in restoring fertility to degraded land is well known. There are opportunities to combine reclamation with production.

The first step is to establish a full forest cover, including at least some nitrogen-fixing species, initially with protection from grazing and allowing all plant residues to reach the soil. As soon as a check of erosion and satisfactory build-up of soil organic matter has been achieved, agroforestry provides ways of combining continued erosion control with productive use.

The techniques and products can vary widely. Selective and closely regulated cutting for fuelwood is one possibility, controlled grazing or cut-and-carry fodder removal another. Both have been successfully combined in

India (Mathur et al., 1979). For the reclamation of severely degraded hills in north Vietnam, a system advocated is to remove trees in contour strips and return these to cultivation, leaving the established trees as belts for conservation and continued fertility improvement (Poulsen. 1984; Young, 1985b).

Near Mombasa, Kenya, coral limestone left bare by quarrying has been restored through planting of *Casuarina equisetifolia:* a small area has been converted into a nature reserve, on which mature natural woodland and a humic topsoil have developed.

Agroforestry in watershed management

Some notable successes have been achieved through watershed planning and management, the integrated control of land use throughout a river catchment. The essence is to apply sound land-use planning to the whole of the catchment, with particular attention to erosion control and water management. Adequate mechanisms for control of land use and management practices are essential, combined with the cooperation of the land users.

To date, most such schemes have been based on judicious combinations of agriculture, erosion-control structures and protective forestry, the last particularly in steep first-order catchments and sometimes along river banks. There is considerable potential, but little experience, for including agroforestry among the range of land uses included in such planning (Baumer, 1984; Vergara, 1985; Sheng, 1986, pp. 85-9).

The suggestion of Sheng (1986, pp. 55-60) that agroforestry should occupy sites intermediate in steepness between those for agriculture and forestry rests on too simplistic a notion of the range of practices. Conversely, it is unrealistic to think of covering an entire watershed with agroforestry practices! What is needed is to hold the various agroforestry options in mind when allotting land according to the principles of land-use planning.

An example may be cited from Shillong, in the north-eastern hill region of India (humid monsoonal climate). In the local practice of shifting cultivation ('jhum'), the former fallow period of 20-30 years has been reduced to three to six years. Erosion during the first and second years of cultivation is very severe, typically 150 t/ha/yr. Terracing has been found to be an effective means of control, but requires high labour inputs. An alternative land-use system has been devised, in which slopes are divided into three parts:

Upper slope: retained under natural forest
Middle slope: pasture with fruit trees on individual semi-circular terraces ("hort-pastoral system')
Lower slope: terraced arable use.

A set of 13 experimental watersheds is being monitored at Shillong, including agroforestry land use (Borthakur et al.. 1979; Singh and Singh, 1981).

Table 10. *Agroforestry practices with potential for control of soil erosion.*

Agroforestry practice	Environments in which applicable	Notes
Plantation crop combinations	Humid to moist subhumid climates	Densely planted combinations of agricultural plantation crops with multipurpose trees appear to control erosion effectively on at least moderate slopes
Multistorey tree gardens, including home gardens	Mainly developed in humid and moist subhumid climates, but possible potential in drier regions	Possess an inherent capacity to control erosion through combination of herbaceous cover with abundant litter
Hedgerow intercropping (alley cropping) and barrier hedges	Humid, subhumid and possibly semi-arid climates	A considerable apparent potential to combine erosion control with arable use on gentle to moderate slopes; more speculative potential on steep slopes; experimental data sparse
Trees on erosion-control structures	Any	Supplementary use of trees stabilizes earth structures and gives production from land they occupy
Windbreaks and shelterbelts	Semi-arid zone	Proven potential to reduce wind erosion
Sylvopastoral practices	Semi-arid and subhumid climates, plus some humid (esp. S. America)	Opportunities for inclusion of trees and shrubs as part of overall programmes of pasture improvement
Reclamation forestry leading to multiple use	Any	Potential for planned design and development
Combinations of the above in integrated watershed management	Anv	Substantial opportunities to include agroforestry with other major kinds of land use in integrated planning and management

Summary

A summary of agroforestry practices with potential for the control of soil erosion is given as Table 10.

The first two, plantation crop combinations and multistorey tree gardens, are similar in their nature and effects; both are dense spatial-mixed practices, which achieve erosion control largely through the provision of a large and frequently renewed litter cover. Hedgerow intercropping achieves control in part by checking runoff and soil loss by partly permeable barrier hedges, and in part through the cover provided by prunings. In the practice of trees on erosion-control structures—grass strips, ditch-and-bank structures and terraces—the trees fulfil supplementary functions, stabilizing the structures and making productive use of the land which they occupy.

Windbreaks and shelterbelts, not reviewed here but with a demonstrated potential for control of wind erosion in both agricultural and pastoral systems, are added for completeness. In other sylvopastoral practices, the role of trees in checking erosion is indirect, but potentially substantial where combined with sound pasture management.

The last two items in the table cover agroforestry as a component in land-use planning. Combined with reclamation forestry, agroforestry can contribute to an evolution towards productive land use. More generally, all agroforestry practices can and should be included as an element in integrated watershed management and land-use planning.

Considerable research is needed if this potential is to be fulfilled effectively. Research requirements are discussed in Chapter 16.

Part HI. Agroforestry for Maintenance of Soil Fertility

it *was planted in a good soil by great waters, that it might bring forth branches, and that it might bear fruit.* Ezekiel xvii.8

Chapter 7
Soil Fertility and Soil Degradation

We have stressed above that the major adverse effect of soil erosion is lowering of fertility, and that this is the main reason why measures should be taken for its control. The hazard of water erosion is at its most serious on sloping land, in virtually all climates, that of wind erosion on land of any slope in the semi-arid zone. In these two, very extensive, sets of environmental conditions, control of erosion is an essential step in maintaining soil fertility.

It is, however, only one step. Land on which there is no substantial erosion hazard, level or nearly level land in the subhumid and humid zones, is frequently subject to soil degradation or lowering of fertility, originating for the most part in what is loosely described as 'over-cultivation'. The potential of agroforestry to reduce or eliminate such lowering of soil fertility is at least as important as that of controlling erosion.

In reality the two problems are not independent. Most land is liable to some degree of erosion and to other forms of soil degradation, both leading to lowering of fertility and loss of sustainability. On level ground, it is fortunate that one cause of fertility loss, that of erosion, is absent. On sloping lands, water erosion is more likely to be the main cause of fertility loss, but most other forms of soil degradation will also be present. In this section, we are concerned with more general soil problems, applicable to lands that are subject to soil erosion but also to areas where there is no erosion hazard or where erosion has successfully been controlled.

Land productivity and soil fertility

Land productivity is the capacity of land to support the growth of useful plants, including crops, trees and pastures, on a sustained basis. It is a property not of soil alone but of land, where land refers to all features of the physical environment that affect potential for land use. As well as soils, land includes elements of climate, hydrology, landforms, vegetation and fauna. It is impossible to consider the productivity of a soil in isolation from other factors.

Climate and landforms for the most part are not open to modification by man. This applies also to some soil properties, such as profile depth and texture. However, many soil properties can be modified, for better or worse, by land use and management. It is this fact which accounts for the major role of soils in agricultural research and farm management.

Soil fertility is therefore the capacity of soil to support the growth of plants, on a sustained basis, under given conditions of climate and other relevant properties of land. The inclusion of a sustained basis in this definition refers to the capacity for continuing support for plants. Some initially productive soils have unprotected stores of nutrients and rapidly lose their fertility if transferred from natural vegetation to managed ecosystems. Others, notably nitosols on basic rocks, possess natural recuperative powers, enabling them to restore nutrients from rock weathering.

A narrower view of fertility is sometimes encountered, namely the content of available nutrients. This leads to a myopic view of soil management, to the neglect of physical and biological properties. It is better to refer to this aspect as nutrient content.

Problems of soil degradation and low soil fertility

Decline in soil fertility

The recognized forms of soil degradation are erosion, physical, chemical and biological degradation, salinization and pollution, where chemical degradation includes both acidification and lowering of nutrient content. They are closely linked: biological degradation influences both soil physical properties and nutrients, whilst erosion is a cause of both biological degradation and loss of nutrients.

All these forms of degradation lead to lowering of soil fertility and land productivity. However, it is the combined effect of lowering of soil organic matter, deterioration of physical properties, lowering of nutrient content and (in some cases) acidification that is commonly referred to as decline in soil fertility.

A number of governments and international agencies have made estimates of the proportions of agricultural land suffering from 'slight, moderate and severe' soil degradation. Viewed as precise figures, they are of very dubious value, since no soil-survey organization has yet systematically applied objective methods of assessing soil degradation. Still less can we distinguish where fertility is still declining from where a condition of low-level equilibrium has been reached. A start has been made in devising methods (FAO, 1979). Degradation assessment is an aim of the Global Environmental Monitoring System (GEMS) of the United Nations Environment Programme (UNEP), and attempts are being made to include it in the Soils and Terrain data base of the International Society of Soil Science.

Be that as it may, there can be no doubt that over very large areas under rainfed agriculture in the tropics and subtropics, soil fertility is less than it was 10, 20 or 50 years ago. Older farmers can be prompted to express this view.

In the present context, it is appropriate to cite experience in applying the method of agroforestry diagnosis and design. Following the identification of distinctive land-use systems, this method is directed first at finding out the kind and severity of problems existing in these systems, and then at diagnosis of their causes. It has been applied, for example, within the All-India Coordinated Research Programme in Agroforestry and the ICRAF Agroforestry Research Networks for Africa. Decline in soil fertility, sometimes expressed as low crop yields, is one of the most frequent problems observed over a wide range of environments. In the causal chains identified during the stage of diagnosis, it is very common to find elements such as those in Figure 4.

Soil degradation not only lowers the crop yields obtainable on the basis of intrinsic soil fertility; it can also substantially reduce the response to fertilizers or other inputs. This lowers the economic margin on fertilizer application, tending to perpetuate the situation of low inputs with low outputs.

A partial exception to the above generalization is the case of swamp rice cultivation. On the one hand, this system contains natural mechanisms for maintenance of soil fertility; on the other, at least some use of manures and fertilizers is now normal in many countries. There are certainly problems of decline in soil fertility, but these are of a distinctive nature.

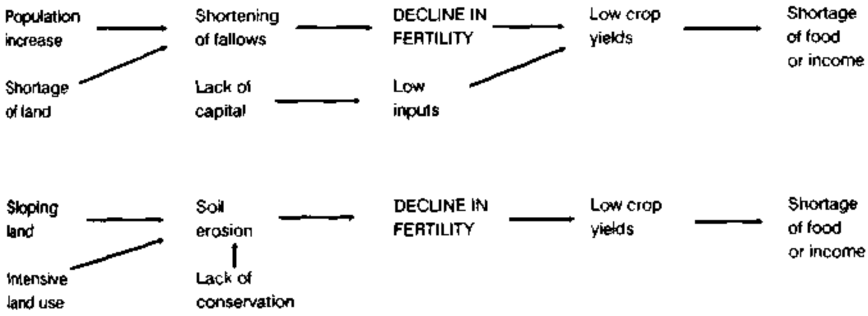


Figure 4. Chains of cause and effect linked to decline in soil fertility

Low soil fertility

The problem of inherently low soil fertility is distinct from that of degradation of formerly fertile soils. Population increase has led to many areas that were formerly under natural forest or pastures being taken into cultivation, the so-called 'marginal lands'. Among the most commonly encountered problems of low natural soil fertility are:

- acidity
- low nutrient content in general
- deficiencies in specific nutrients, most commonly nitrogen and phosphorus
- adverse physical properties.

The most widespread soil types that are commonly cultivated but offer substantial problems of low soil fertility are:

1. The highly weathered, strongly leached, red and yellow soils of the humid tropics or rain forest zone (ferralsols and acrisols). These offer problems of acidity, rapid leaching, low nutrient retention once topsoil organic matter is reduced, and phosphorus fixation.
2. Plateau sandveld soils, the highly weathered, poorly structured, sandy soils of the subhumid zone (p. 6). These offer problems of low nutrient content, poorly developed soil structure and, in some cases, acidity.
3. Black, cracking clays (vertisols). The principal problems are linked to the high content of swelling clays, including the large size of structural aggregates and low porosity (Young, 1987d).

Each of the above soil types is included in the research networks of the International Board for Soil Research and Management (IBSRAM).

Diagnosis of soil fertility problems in planning for agroforestry

Low soil fertility and decline in soil fertility are distinct problems. They are linked in that an inherently infertile soil is likely to suffer more rapid degradation.

For some purposes, both situations present a similar problem: a nutrient deficiency or poor structure have the same effects whatever their origin. However, in ameliorating problems through soil management, the two situations are distinct. If the soil was originally more fertile and has been degraded, there is *a prima facie* assumption that fertility can be upgraded by land-use practices that more nearly resemble the natural ecosystem, e.g., by the introduction of trees. If the soil was inherently infertile, the task is intrinsically harder. In the former case we are working with nature, in the latter, trying to improve upon it.

Diagnosis of the problem of low crop yields should therefore distinguish between *low soil fertility,* caused by natural soil conditions, and *decline in soil fertility,* brought about by past land use.

Management options for maintaining soil fertility

Practices other than agroforestry

Some lands are newly settled, others have been farmed for hundreds or thousands of years. Many methods have been devised, traditional and modern, for maintaining soil fertility, of which agroforestry is one. For every method there are constraints which limit its applicability as a practical management option in less-developed countries.

Table 11 lists 10 traditional practices and 2 modern ones, plus agroforestry. Three kinds of constraint to their application under practical farming circumstances in the modern world are shown: type of land, extent of land and supply problems.

A constraint of type of land means that the practice is only applicable on land with certain properties. This applies to use of naturally sustainable soils, and to flood irrigation and swamp rice cultivation. Naturally sustainable soils are those derived from basic rocks (nitisols) which have the capacity to renew fertility by weathering of rock minerals and can sustain nearly continuous cultivation; they are of limited extent, carry high population densities, and are now so intensively used that they are no longer free from degradation.

Renewal of fertility by the nutrients carried in flood waters was a feature of some of the earliest forms of agriculture, now largely lost through flood control.

Swamp rice cultivation possesses natural methods of fertility renewal, as well as responding well to inputs. It already supports about half the population of less-developed countries, largely in Asia, and is steadily being

Table 11. *Management practices for maintenance of soil fertility, with constraints to their application.*

	Land constraints		Supply constraints
	Type	Extent	
— Cultivating more land		*	
— Fallowing (shifting cultivation)		*	
— Use of naturally sustainable soils	*		
— Return of crop residues			*
— Crop rotation			
— Intercropping			
— Organic manuring: farmyard manure, compost, mulch			*
— Green manuring		*	
— Flood irrigation	*		
— Swamp rice cultivation	*		
— Fertilizer			*
— Minimum tillage			*
— Agroforestry		?	

Note: There are overlaps among the practices as listed above. Shifting cultivation is an agroforestry practice, many kinds of agroforestry are forms of intercropping and agroforestry frequently provides organic manures.

extended. Predominantly found on alluvial lands, it is unrealistic to suppose that the vast labour input needed to construct irrigated terraces, such as those of Java, the Philippines or Nepal, will be developed in other continents. The high productivity per unit area of land makes it certain that this will continue to be a valuable form of development, but one largely confined to valley floors and alluvial plains.

The constraint of extent of land most obviously affects the first practice listed, that of responding to declining crop yields by clearing and cultivating more land. It applies also to green manuring, a form of non-productive improved fallow which has rarely found favour with farmers.

The technique of fallowing, or shifting cultivation, was formerly the most widespread means of restoring the fertility lost in cultivation. It is also the oldest agroforestry practice. Much has been written about shifting cultivation, the basic message being that it is sustainable provided that the fallow periods are of adequate length, but it tends to be soil degrading where fallows are shortened by pressure of population upon land. The relative lengths of cultivation and fallow are expressed in terms of the R factor, the percentage of cultivation within the total cycle:

$$R\% = \frac{\text{Years under cultivation}}{\text{Years under cultivation plus fallow}} \times 100$$

An early determination of the R factors necessary to maintain soil fertility under shifting cultivation (Nye and Greenland, I960; Young, 1976, p.114) gave the values of 17-33% for rain forest and 5-11% for savanna (burnt).

A more comprehensive assessment, based on a combination of published evidence and questionnaire enquiry, was carried out as part of an FAO study of population-carrying capacities. This was based on the *rest-period requirement* defined as the R factor necessary to maintain soil fertility under annual cropping. Estimates of rest-period requirements were obtained for the three major ecozones of the tropics, rain forest, savanna and semi-arid: for FAO soil types, combined into 10 groups; and for three levels of inputs: low (traditional farming), intermediate (improved farming) and high (modern, high-technology, farming). The results are shown in Table 12.

There are many problems in making these estimates, primarily because it is rarely known whether, or to what extent, soils are degrading under current land use. The results, nevertheless, serve to show orders of magnitude. The dominant feature is the low proportion of cultivation at which fertility can be sustained at low input levels, particularly on the more extensive soil types. Even at the level of intermediate inputs, the highest which it is reasonably possible to attain in the foreseeable future, there are still requirements of between one and two years in three under fallow.

Table 12. *Rest period requirements of tropical soils. All values refer to the cultivation factor, R, expressed as a percentage. Numbers in column headings are growing periods for annual crops, in days (Young and Wright, 1980).*

	Low Inputs			Intermediate Inputs			High Inpats		
Soil tvpe (FAO)	Rain forest /.one 270-365	Sav-anna zone 120-269	Semi-arid Zone 75-119	Rain forest zone 270-365	Sav-anna zone 120-269	Semi-arid zone 75-119	Rain forest zone 270-365	Sav-anna zone 120-269	Semi-arid zone 75-119
Rcgosols and Arenosols	10	15	20	30	35	45	50	65	50
Fcrralsols	15	15	20	35	35	40	70	70	75
acric	5			10			60		
Acrisols	15	15	20	40	35	60	65	65	75
Lixisols	25	30	35	50	50	55	70	75	75
Cambisols	35	50	40	65	60	85	85	80	80
Nitisols									
dystric	25	30	40	55	80	70	90	90	90
eutric	40	55	75						
Vcrtisols	40	55	45	70	75	75	90	90	90
Fluvisols and Glcysols	60	70	90	80	80	90	90	90	90

These data conflict with the fact that at present the predominant form of tainted agriculture over large parts of less-developed countries is more or less continuous cultivation. The implication is that soil fertility either is being degraded or has reached a condition of low-level equilibrium, stable but with low yields. Neither situation meets the definition of sustainability. Non-productive fallowing is no longer a practical management option for sustaining soil fertility.

Four other practices in Table 11 are limited in their applicability by supply constraints. The return of crop residues is certainly of proven value, but many farmers have other uses for these, and there are sometimes pest-control reasons for their removal. Organic additions, including farmyard manure, compost and mulch, are of considerable and proven value, but at levels of application such that only a small proportion of farmland can be treated; it has frequently been shown that 5-10 t/ha/yr of farmyard manure sustains soil fertility, whereas 1-2 t does not.

No single technical improvement has raised crop yields as much as that of fertilizers, but a supply constraint is extremely widespread. It arises not because of absolute shortage at a world scale but because of the many problems which in practice prevent supplies reaching the farmer: lack of foreign currency at the national level, lack of loan facilities, or an inefficient distribution system.

The second modern technology listed, minimum tillage, has been proven as an efficient means of soil-fertility maintenance, including erosion control, under experimental conditions and thus high standards of management, in the humid to moist subhumid tropics. It is quite widely practised under mechanized agriculture in the temperate zone, but has rarely been adopted by farmers in the tropics. Its basic requirement of herbicides for weed control poses a direct supply problem, coupled with the environmental hazard of distributing toxic substances to small farmers. Whilst of high potential from a technical point of view, it remains problematic for development unless and until successfully adopted by farmers.

Neither land nor supply constraints apply to the practices of crop rotation. However, rotation and intercropping both are means of efficiently sharing limited soil resources rather than restoring them.

Six of these non-agroforestry practices, in combination, possess considerable potential to improve or sustain soil fertility over large areas of the tropics: crop rotation, intercropping, return of crop residues, organic additions, swamp rice cultivation and fertilizer. The remainder are either of limited and decreasing applicability in the modern world, or in one case unproven. With the exception of the two practices which improve the efficiency of soil resource use, rotation and intercropping, all are subject to substantial constraints, of type of land, extent of land, or supply of material.

Agmforestry as a practical management option

To what extent do the same constraints apply to agroforestry? This question is critical as a prerequisite for research into the benefits, for soil fertility as in other respects, of agroforestry. The more widely applicable is agroforestry, as a practical option in farm management, the more necessary it is to appraise its benefits and improve techniques.

Type of land. At an early stage in the modern awareness of agroforestry, it was said to be particularly suited to 'marginal' lands, those with environmental hazards such as drought, erosion or low soil fertility. If this were so, then the extent of its potential application would be substantially reduced, although large areas would still remain.

Evidence from the ICRAF agroforestry systems inventory shows that this is not the case. Agroforestry systems are found in humid regions, on gently sloping land and on some of the most fertile soils, as well as in more difficult environments. For example, the Chagga home gardens system is found on relatively rich soils, whilst systems of intercropping and grazing under coconuts occur mainly on level, alluvial land, in both cases under plentiful rainfall (Nair, 1984-88, 1987b). Current agroforestry research is found in fertile areas as well as marginal, for example on the Lilongwe Plain of Central Malawi, the richest agricultural area in the country.

The reason for the early presumption was that land-use problems were generally most serious in marginal lands, and these were where help from agroforestry was first sought. In the early years of the ICRAF Collaborative Programme, steeply sloping environments were over-represented, and they are also common in the systems inventory. Certainly, there arc some sets of environmental and social conditions in which the potential for agroforestry is particularly high: densely populated, steeply sloping lands are one such, frequently having problems of erosion, fertility decline, forest clearance and fuelwood shortage (Young, 1986d, 1989d).

For one major environment, that of alluvial plains, the potential of agroforestry is probably less than on erosional landforms, although research may prove this to be false. Several systems of combining trees with swamp rice cultivation are known (Tran Van Nao, 1983; Weerakoon and Gunasekera, 1985).

Thus agroforestry is potentially applicable to a very wide range of types of land in the tropics. Different practices arc applicable in different environments, for example, multipurpose windbreaks in semi-arid areas, or trees for soil conservation on sloping lands. Research into land evaluation for agroforestry is needed to identify those kinds of environment which are particularly suited to specified agroforestry practices (Young, 1984a).

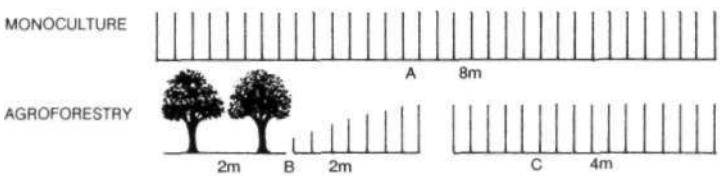
Extent of land. A constraint of extent of land was noted to apply to fallowing and green manuring, meaning that these practices required land over and ahove that needed for productive purposes. In the context of agroforestry, there are two critical questions:

1. If trees are grown with herbaceous plants (crops or pastures), is the output from the herbaceous plants reduced?
2. If the answer to the above is yes, then does the output from the trees more than compensate for the loss in production from the herbaceous plants?

Expressed in economic terms, the first question becomes, in a given combination of trees with herbaceous plants, are these two components complementary (the presence of one increases output from the other), supplementary (no mutual interactions), or competitive (the presence of one reduces output from the other)?'

There are examples, from traditional systems and recent research, of both gains and losses in crop or pasture production as a result of the presence of trees. If it were to be found that under a wide range of environments and designs trees led to a loss of food-crop production, then this would seriously reduce the potential of agroforestry. In some spatial agroforestry practices, such as boundary planting or trees on conservation works, the tree component occupies otherwise unproductive land. In others, notably hedgerow intercropping, there is an inevitable reduction in the area under crops (perceived by laymen as one of the major obstacles to agroforestry). Also, a fall-off in crop yield close to the tree/crop interface is commonly observed.

The question then becomes whether an increased yield per unit area under crop, brought about by the erosion-control and fertility-enhancement effects of the trees, more than compensates for the loss of land under crop plus any reduction in yield close to the interface. This is illustrated in Figure 5, which compares monocropping with a spatial-zoned agroforestry system in which trees take up 25% of the land. All cases assume a halving of crop



Crop yield and production (arbitrary units):

	CASE 1 Yield per m	CASE 1 Production	CASE 2 Yield per m	CASE 2 Production	CASE 3 Yield per m	CASE 3 Production
MONOCULTURE: Unit A	100	800	100	800	100	800
AGROFORESTRY: Unit B	50	100	70	140	90	180
Unit C	100	400	140	560	180	720
Total crop		500		700		900
Tree		200		200		200

Value 1 crop unit = 1 money unit
1 tree unit = 0.75 money units

	CASE 1	CASE 2	CASE 3
MONOCULTURE	800	800	800
AGROFORESTRY	650	850	1050
	CASE 1: Lost production	CASE 2: Reduced crop production but economic compensation	CASE 3 Inreased crop and total production

Figure 5. Tree/crop displacement, yield, production and value.

yield over a 2 m interface. In Case 1, the crop yield away from the interface is no higher than in the control; crop production is lower, as is the economic return. In Case 2, the presence of trees raises crop yield by 40% away from the interface; this is not sufficient to compensate for the combined effects for displacement plus interface reduction, and crop production is again lower, but this is slightly more than compensated for in money terms by the revenue from the trees. Case 3 shows an 80% increase in yield per unit area under crop (a realistic possibility as a result of erosion control) leading to a 12,5% increase in crop yield for the area as a whole.

The cases in Figure 5 can be closely matched in those rotational agroforestry systems in which there is a pure alternation between tree and crop, giving displacement in time. This does not apply to the taungya practice, since crop production overlaps tree growth. In spatial-mixed systems the interface is more or less ubiquitous and there is often very little spatial displacement or reduction in area of crop: the question then takes the simpler form of whether crop yield is higher with trees than without. Which of these three cases is likely to prevail under different circumstances is a basic question for agroforestry research.

Supply constraints. The main inputs required in agroforestry, additional to those in agriculture, are supplies of tree germplasm and seedlings. Whilst there may be temporary local shortages, there are no intrinsic supply constraints. Local tree nurseries are simple and relatively cheap to construct. There is nothing in agroforestry development projects comparable to the level of expense involved in, say, construction of dams or roads. The supply constraint of fertilizers is likely to be reduced or unchanged.

In present-day agroforestry development, the major costs are research and training. Whilst these will continue to be necessary, their magnitude at present is a temporary phenomenon, stemming from the rapid growth in awareness of the potential of agroforestry for development. With respect to inputs and capital, therefore, agroforestry is a relatively undemanding form of development, with no serious supply constraints.

Agroforestry is also a highly practicable management option at the farm level. It requires nether substantial capital nor machinery, and the necessary skills for tending trees can be learnt by farmers with limited formal education.

Summary. The position of agroforestry with respect to the three constraints to application is therefore:

Type of land: Given the number of different practices, agroforestry is applicable over a wide range of land types, with greater potential on some than others.

Extent of land: Many agroforestry practices involve some degree of reduction in area of crops through displacement by trees. The loss of cropped area can be compensated either if the yield per unit area under crop is higher, or if value of production from the tree component compensates for loss of crop production. Which of these situations applies in differing circumstances is a matter for research.

Supply: Agroforestry does not require inputs that are in short supply or which involve hard-currency imports, and is a relatively inexpensive form of development both for government and the farmer.

Both at governmental and farm levels, therefore, agroforestry is very widely applicable as a practical management option.

AGROFORESTRY AS A PRACTICAL MANAGEMENT OPTION

- Type of land: The range of practices allows agroforestry to be applied over a wide variety of environmental conditions.
- Extent of land: Most agroforestry practices, other than rotational, are not land-extensive.
- Supply of inputs: Agroforestry does not require inputs that are costly or in short supply. It is a relatively inexpensive form of land development.
- Technology: The technology employed, that of managing trees, is generally familiar to farmers.
- Agroforestry is therefore widely applicable as a practical management option.

Chapter 8
Effects of Trees on Soils

How we know that trees improve soils

Underlying all consideration of the role of agroforestry in maintenance of soil fertility is the fundamental proposition that trees improve soils. Before examining the processes and evidence in detail, it is worth setting out how we know that this is true.

1. The soil that develops under natural woodland or forest, the classic brown earth of temperate regions or red earth of the tropics, is fertile. It is well structured, has good moisture-holding capacity, is resistant to erosion and possesses a store of fertility in the nutrients bound up in organic molecules. From time immemorial, farmers have known that they will get a good crop by planting on cleared natural forest.
2. The cycles of carbon and the major nutrients under natural vegetation have been demonstrated, most notably in rain forest but also in savanna and semi-arid ecosystems. These cycles are relatively closed. Thus, not only can we observe the fact that trees maintain soil fertility, but the details of how this is achieved are known.
3. The practice of shifting cultivation provides a demonstration of the capacity of forest to restore fertility. Nowadays this practice is often treated as environmentally undesirable, and certainly this is so once population pressure on land has forced the shortening of fallows. Given enough land and thereby length of fallow, however, this is a sustainable practice, and provides a demonstration of the capacity of forest or woodland to restore the fertility lost during cultivation.
4. Reclamation forestry, the afforestation of eroded or otherwise degraded land, has demonstrated the power of trees to build up soil fertility, notably in India.
5. Finally, among these background considerations, is the almost invariable decline in soil fertility that follows complete forest clearance.

Tree-soil transects

Further evidence for the effects of trees on soils comes from comparing soil properties under the canopy of individual trees with those in the surrounds without a tree cover. For *Acacia albida,* cases of 50-100%

increases in organic matter and nitrogen under the canopy are known, together with increased water-holding capacity (Felker, 1978). In semi-arid climates it is common to find higher soil organic matter and nutrient content under tree canopies than in adjacent open land (Table 13). Maize and sorghum in pot samples from soils under trees in northern Nigeria grew 2 to 3 times faster than in soil with no trees; the order of fertility was *Azadirachta indica* > *Prosopis juliflora* = *Eucalyptus camaldulensis* > no trees (Verinumbe, 1987).

'This approach has been extended by the technique of tree-soil transects, lines of soil samples taken from the trunks of trees to land beyond the

Table 13. *Soil properties beneath trees.*

A. North-west India, semi-arid climate (Aggarwal, 1980)

Available nutrients at two soil levelis (kg/ha)	Under *Prosopis cineraria*	Under *Prosopis juliflora*	Open field
N: 0-15 cm	250	203	
15-30 cm	193	212	196
P: 0-15 cm	22	10	8
15-30 cm	10	5	4
K: 0-15 cm	633	409	370
15-30 cm	325	258	235

B. Northern Nigeria, dry savanna climate (Radwanski and Wickens, 1981)

Soil property	Fallow under *Azadirachta indica*	Bare fallow farmland
pH	6.8	5.4
Organic C(%)	0.57	0.12
Total N(%)	0.047	0.013
P(ppm)	68 (lower)	195
TEB(me/100g)	2.40	0.39
CEC (me/100 g)	2.25	1.70
Base saturation (%)	98	20

C. California, USA, arid with groundwater (Virginia, 1986)

Nutrients (mg/kg)	Under *Prosopis glandulosa*	Beyond canopy
NO,—N	195	62
P0$_4$—P	7.7	0.8

canopy. To date, it has been applied to natural savannas. In the moist subhumid zone of Belize, tree-soil transects of broadleaf savanna trees showed considerable enrichments in nitrogen, phosphorus, potassium, calcuim and other bases under trees, the differences starting near canopy margin and increasing towards the trunk (Figure 6A). Isopleths of calcium, magnesium and base saturation were mapped by grid sampling of topsoils.

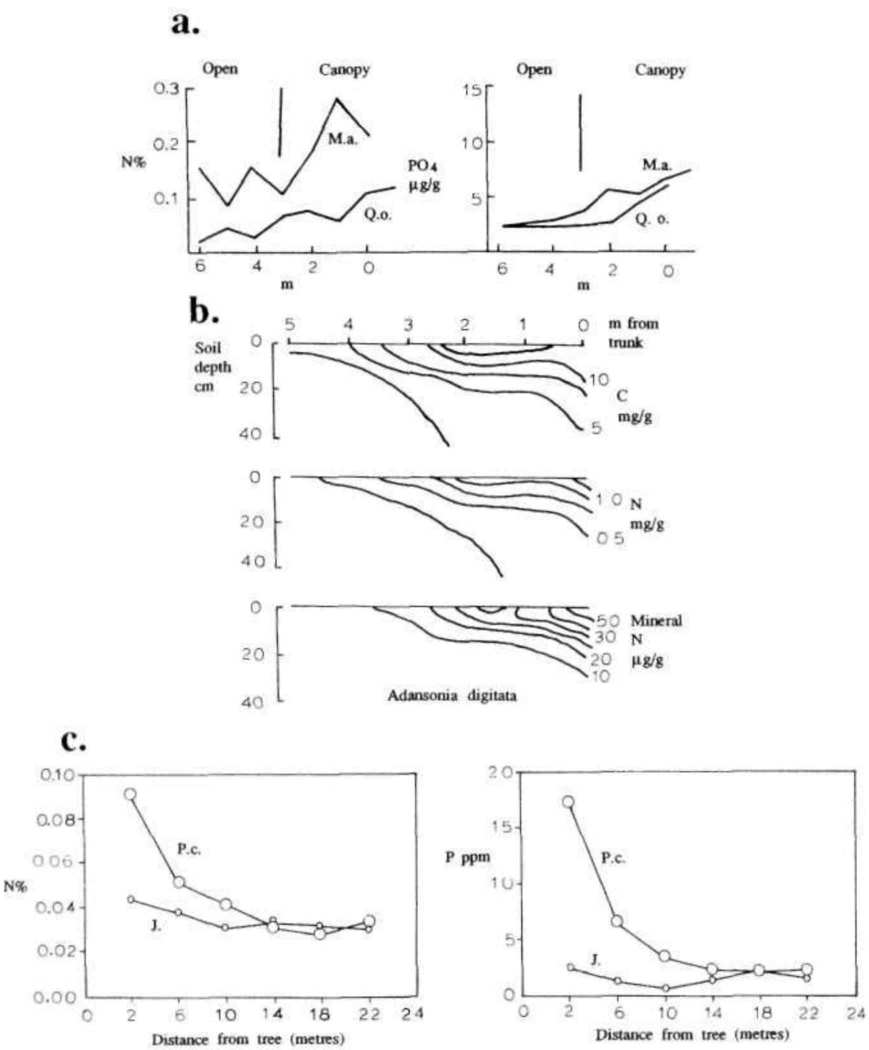


Figure 6. Tree-soil transects. A. Savanna, Belize, topsoil. M.a. = *Miconia albicans*, Q.o. = *Quercus oleoides* (after Kellman, 1980). B. Semi-arid grassland, Senegal (after Bernhard-Reversat, 1982). C. Tlaxcala, Mexico. P.c. = *Prunus capuli*, J. = *Juniperus* spp. (after Altieri et al., 1986).

Sampling in depth showed that for one species, the topsoil enrichment was apparently at the expense of lower values at 20—40 cm, but for others the positive effect of the tree continued in depth. Root excavation showed unexpectedly shallow systems, so these differences were attributed not to abstraction of elements from deep soil horizons but to the cumulative effect over time of preferential retention of atmospheric nutrient inputs, leading to a richer plant-soil nutrient cycle under the tree (Kellman, 1980).

On a sandy luvisol in the semi-arid zone of northern Senegal, soil organic carbon, total nitrogen and the mineral nitrogen flux showed a progressive decrease from the trunk to the canopy margin under *Acacia Senegal, Balanites aegyptiaca* and baobab *(Adansonia digitata)* (Figure 6B). This was considered either to be a primary effect of tree litter, or a secondary effect, reduced evapotranspiration allowing better growth of herbaceous plants (Bernhard-Reversat, 1982). In Tlaxcala, Mexico (subhumid climate), trees with intercropped maize influenced soil properties to a 6-10 m radius; under *Primus capuli* and *Juniperus* sp., nitrogen (N) was 1.5-3 times higher under trees, available phosphorus (P) 4—7 times, potassium (K) 1.5-3 times, and calcium, magnesium, carbon and cation exchange capacity also increased (Altieri et al., 1986) (Figure 6C).

Current research in the semi-arid areas of the Tsavo West National Park, Kenya, has shown substantially higher organic matter, nitrogen, microbial activity and, especially, phosphorus under canopies of baobab *(Adansonia digitata)* and *Acacia tortilis.* Possible causes are bird droppings and elephant dung. Soil physical properties were better under trees, and moisture was retained longer. Grass growth was nearly twice as fast and grass species composition quite different. The soil microbial biomass was 30% higher (A.J. Belsky, personal communication).

Such soil enrichment could result from many causes: stemflow from the tree trunk, preferential trapping of atmospheric inputs, enhanced nutrient uptake from depth, reduction in leaching loss by tree roots, or effects of animals and birds. Animals (wild and domesticated), like humans, prefer to stand under trees when not engaged in activities that require otherwise; they therefore selectively concentrate nutrients from the surrounding land on which they graze.

This is a fertile area for research! The basic soil-transect technique could also be applied to lines of blocks of trees in agroforestry systems, and to newly planted trees as well as natural vegetation. Examples are transects across tree-crop interface experiments, hedgerows in hedgerow-intercropping systems and shelterbelts. There is scope for much ingenuity in design to separate the various causes of soil differences.

Processes by which trees improve soils

Table 14 and Figure 7 show the known or possible effects of trees on soils. These refer to a tree or shrub cover in general, not specifically within

Table 14. *Processes by which trees maintain or improve soils (not all of the listed effects are proven; see text).*

Processes which augment additions to the soil:

- maintenance or increase of soil organic matter through carbon fixation in photosynthesis and its transfer via litter and root decay
- nitrogen fixation by some leguminous and a few non-leguminous trees
- nutrient uptake: the taking up of nutrients released by rock weathering in deeper layers of the soil
- atmospheric input: the provision by trees of favourable conditions for input of nutrients by rainfall and dust, including via throughfall and stemflow
- exudation of growth-promoting substances by the rhizosphere.

Processes which reduce losses from the soil:

- protection from erosion and thereby from loss of organic matter and nutrients
- nutrient retrieval: trapping and recycling nutrients which would otherwise be lost by leaching including through the action of mycorrhizal systems associated with tree roots and through root exudation.
- reduction of the rate of organic matter decomposition by shading.

Processes which affect soil physical conditions:

- maintenance or improvement of soil physical properties (structure, porosity, moisture retention capacity and permeability) through a combination of maintenance of organic matter and effects of roots
- breaking up of compact or indurated layers by roots
- modification of extremes of soil temperature through a combination of shading by canopy and litter cover.

Processes which affect soil chemical conditions:

- reduction of acidity, through addition of bases in tree litter
- reduction of salinity or sodicity.

Soil biological processes and effects:

- production of a range of different qualities of plant litter through supply of a mixture of woody and herbaceous material, including root residues
- timing of nutrient release: the potential to control litter decay through selection of tree species and management of pruning and thereby to synchronize nutrient release from litter decay with requirements of plants for nutrient uptake
- effects upon soil fauna
- transfer of assimilate between root systems.

agroforestry systems. They range between proven and quantitatively demonstrated effects at one extreme to plausible but unproven hypotheses at the other. The box on p. 98 shows the status of each suggested effect, many of which are discussed in more detail in later sections.

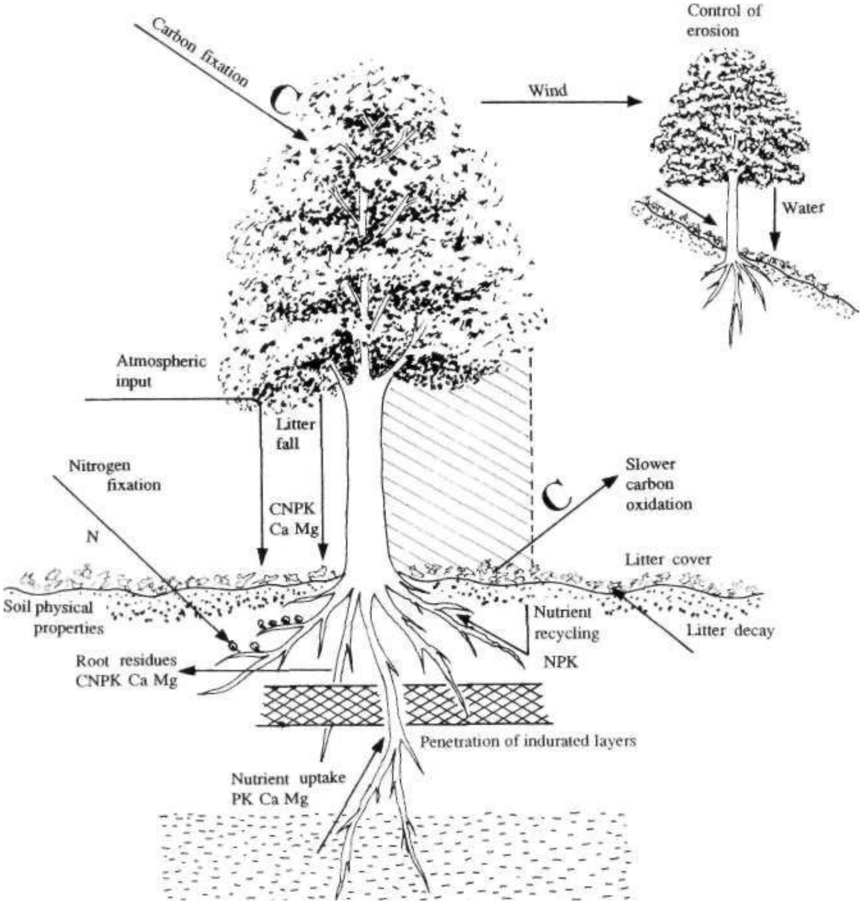


Figure 7. Processes by which trees improve soils.

HOW TREES IMPROVE SOILS

- increasing inputs (organic matter, nitrogen fixation, nutrient uptake)
- reducing losses (organic matter, nutrients) by promoting recycling and checking erosion
- improving soil physical properties, including water-holding capacity
- beneficial effects on soil biological processes.

Processes which augment additions to the soil

Maintenance or increase of soil organic matter. This is proven and widely demonstrated, including through build-up of organic matter in forest fallows, reclamation forestry and chronosequences of soil development on recent sediments. It has been shown in quantitative terms through studies of organic matter cycling under natural forest.

Nitrogen fixation. This is proven, both indirectly through soil-nitrogen balance studies and directly by observation of nodulation and 15-N tracer studies.

Nutrient uptake. This is a plausible hypothesis, not specifically demonstrated. The hypothesis is that in general trees are more efficient than herbaceous plants in taking up nutrients released by weathering in deeper soil horizons. Potassium, phosphorus, bases and micronutrients are released by rock weathering particularly in the B/C and C soil horizons into which tree roots often penetrate. The strong gradient in nutrient content between forest topsoils and subsoils indicates recycling through litter, although other processes are also involved. Direct proof would be difficult.

Atmospheric input. Atmospheric deposition makes a significant contribution to nutrient cycling, greater in humid regions than dry. It comprises nutrients dissolved in rainfall (wet deposition) and those contained in dust (dry deposition). Trees do not increase rainfall but they do reduce wind speed and thereby provide preferential conditions for deposition of dust.

A more complex situation applies to the nutrients contained in throughfall and stemflow, the former being rain dropping from canopy leaves, the latter that flowing down stems. These nutrient amounts are substantial, in some forests being the major source (exceeding litter) for potassium, sodium and sulphur. However, it is difficult to determine what proportions of dissolved nutrients originate from leaf leaching (and thus recycling) and from washing (and thus atmospheric net input), and estimates range widely (Parker, 1983).

It would be useful to make experimental comparisons between nutrient deposition on forested and open sites. An agroforestry element could be added by inclusion of sites with belts of trees (e.g. windbreaks, hedgerow intercropping).

Exudation of growth-promoting substances by 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.

Processes which reduce losses from the soil

Protection from erosion. This was discussed in Part II of this review. The salient points are: (1) the major adverse effect of erosion is loss of soil organic matter and nutrients with consequent lowering of crop yields; (2) a forest cover reduces erosion to low levels, primarily through the effect of the ground surface cover of litter and understorey vegetation, the protection afforded by the tree canopy being relatively slight.

Nutrient retrieval. It is commonly supposed that tree root systems intercept, absorb and recycle nutrients in the soil solution that would otherwise have been lost in leaching, so making the nutrient cycle more closed. The mycorrhizal systems associated with the tree roots are an agent in this process through their penetration of a large proportion of the soil volume, leading to uptake of nutrients which can only move 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; International Livestock Centre for Africa (ILCA), 1986). Direct demonstration of the nutrient-retrieval process would require isotopic tracer studies, comparing the uptake of labelled fertilizer between tree and non-tree plant covers.

Reduction of the rate of organic matter decomposition. It is known that the rate of loss of humified organic matter is lower in forest than under agriculture. Shading by the canopy and litter cover of trees, giving reduced temperatures, is one reason for this effect.

Processes which affect soil physical conditions

Maintenance or improvement of soil physical properties. The superior soil structure, porosity, moisture characteristics and erosion resistance under forest is well documented, as is their decline on forest clearance. Porosity is a key to many other physical properties: pores of 5-50 |xm in diameter determine available water-holding capacity, whilst those over 250 . m 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 (Lall and Greenland, 1979).

Breaking up of compact or indurated layers by roots. This potential of trees has been shown under forest plantations.

Modification of extremes of soil temperature. There is experimental evidence from studies of minimum tillage that a ground surface litter cover greatly reduces the extremely high ground surface temperatures, sometimes over 5()°C, that are experienced on bare soils in the tropics; and that high temperatures adversely affect crop growth (Harrison-Murray and Lai, 1979). The leaf litter cover produced by trees can be expected to have similar effects.

Processes which affect soil chemical conditions

Reduction of acidity. Trees tend to moderate the effects of leaching through addition of bases to the soil surface. However, whether tree litter can be a significant means of raising pH on acid soils is doubtful, owing to the orders of magnitude involved, except through the release of bases that have been accumulated during many years of tree growth, as in forest clearance or the *chitemene* system of shifting cultivation.

Reduction of salinity or sodicity. Afforestation has been successfully employed as a means of reclaiming saline and alkaline soils. For example, under *Acacia nilotica* and *Eucalyptus tereticornis* in Karnal, India, lowering of topsoil pH from 10.5 to 9.5 in five years, and of electrical conductivity from 4 to 2, has been reported, but with tree establishment assisted by additions of gypsum and manure (Gill and Abrol, 1986; Grewal and Abrol, 1986). Part of the soil improvement in this type of reclamation forestry is no doubt due to drainage improvement by ditches, leading to better leaching. The role of the trees could be tested by comparison with control plots given the same drainage, soil amelioration and other management measures, but without trees.

Soil biological processes and effects

Production of a range of qualities of plant litter. This has the effect of distributing, over time, the release of nutrients mineralized by litter decay. Trees provide both woody and herbaceous residues, and thus a range in quality both of above-ground litter and root residues. Whether any distinctive properties are conferred upon soils by woody residues, or if these contribute differentials to certain fractions of humus, has not been established.

Timing of nutrient release. Given the range in quality of tree residues, their different rates of decay will cause the release of nutrients to be spread over time. In managed systems this release can be partly controlled, through selection of tree species on the basis of rates of leaf decay, and timing of pruning. It is therefore possible partially to synchronize the release of nutrients from litter with the requirements for plant uptake. That this can be achieved is a fundamental hypothesis of the Tropical Soil Biology and Fertility Programme (Swift, 1984, 1985, 1987, in press).

Effects upon soil fauna. Trees greatly modify the kinds and amounts of soil fauna, generally in a direction favourable to fertility. More needs to be learnt about this. A specific indirect effect that has been suggested is that shade trees in plantations, through reduction of weeds by shading, result in less need to use chemical herbicides which adversely affect soil fauna (Beer, 1987).

Transfer of assimilate between root systems. Direct transfer of matter between root systems, possibly via mycorrhizal bridges, has been suggested (Fitter, 1985). If proven, this could be a mechanism for transfer of nutrients from trees to crops.

Adverse effects

Trees can have directly adverse effects on soil properties, whilst other consequences arise when they are grown in association with herbaceous plants. Leaving aside shading, a major problem at the tree/crop interface but unconnected with soils, the main soil-related problems that can arise arc given in Table 15.

Table 15. *Adverse effects of trees on soils.*

- loss of organic matter and nutrients in tree harvest
- nutrient competition between trees and crops
- moisture competition between trees and crops
- production of substances which inhibit germination or growth
- acidification by trees which produce mor-type humus.

Loss of organic matter and nutrients in tree harvest. Of concern in forestry is the depletion of soil resources by fast-growing trees, with consequences for subsequent forest rotations. Trees assemble considerable quantities of nutrients in their biomass, part of which is necessarily removed in harvest. The problem is greatest where there is whole-tree harvesting, most commonly the gathering up of fine timber and litter by local people after 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 frequently conflicts with social necessity—to the local population it appears totally unreasonable! In agroforestry, the soil-improving potential of trees is greatly reduced if both foliage and wood are harvested, for fodder and fuelwood.

Nutrient competition between trees and crops. In general, trees are less demanding of nutrients than crops. The problem is most likely to be serious when trees or shrubs have an established root system which can dominate that of newly planted annual crops. It is desirable that trees in agroforestry should have rooting systems which penetrate deeply but have 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, moisture competition is possibly the most serious problem in agroforestry research and design. Discussion of soil-moisture competition lies beyond the scope of the present review.

Production of substances which inhibit growth or germination. Some *Eucalyptus* species produce toxins which can inhibit the germination or growth of some annual herbs (Power and Fries, 1985). The production of allelopathic substances by tree roots has been suggested as a possible problem in agroforestry, although there is little evidence.

Acidification by trees which produce mor-type humus. This is a known problem in conifer plantations of the temperate zone.

Wherever a decrease in crop or pasture growth close to, or beneath, trees or shrubs is observed, it is important to establish the degree to which this is due to shading, nutrient competition, moisture competition, growth inhibition, or light suppression by leaf litter.

Chapter 9
Soil Organic Matter

Organic matter and soil fertility

Of all the effects of trees, that of maintaining soil organic matter levels through the supply of litter and root residues is the major cause of soil fertility improvement. It is the prime mover, from which stem many of the other soil-improving processes (Table 16).

Table 16. *Effects of organic matter on soil fertility.*

Primary effects	Consequences
Physical effects	
Binding of particles, root action leading to improved structural stability, balance between line, medium and large pores	Improved root penetration, erosion resistance and moisture properties: water-holding capacity, permeability, aeration
Chemical effects	
Nutrient source, balanced supply, not subject to leaching, with slow, partly controllable, release	Including better response to fertilizers, non-acidifying source of N, mineralization of P in available forms
Complexing and enhanced availability of micronutrients	
Increased cation exchange	Better retention of fertilizer nutrients
Improved availability of P through blocking of fixation sites	
Biological effects	
Provision of a favourable environment for N fixation	
Enhanced faunal activity	

Note: See Young (1976), Swift and Sanchez (1984), Lal and Kang (1982). IRRI (1984), Piccolo (1986), Dudal (1986), Johnston (1986).

FUNCTIONS OF ORGANIC MATTER IN MAINTAINING SOIL FERTILITY

- Under all land-use systems: maintains good soil physical conditions, including water-holding capacity.
- Under low-input systems: provides a balanced supply of nutrients, protected against leaching until released by mineralization.
- Under medium- and high-input systems: leads to more efficient use of fertilizers through improved ion-exchange capacity, greater recycling and supply of micronutrients.

The main effects are on soil physical properties and nutrient supply. The physical effects are produced by the action of organic gums and fungal mycelia in binding soil particles into aggregates, and by the growth and decay of root systems. This leads to maintenance of soil structure and structural stability, and a balanced distribution of pore sizes, including both fine (water-retentive) and coarse (transmission) pores. The consequences are a combination of water-holding capacity with permeability and aeration, ease of root penetration and, through stable structure coupled with permeability, erosion resistance. The whole forms an interactive complex of processes, producing favourable physical properties so long as organic matter is maintained; its loss leads to their degradation, and where serious can lead to consequences such as capping, compaction or pan formation.

The major chemical effect is upon nutrient supply, with three favourable aspects: the supply is balanced across the range of primary, secondary and micronutrients; so long as it remains in the form of organic molecules, it is protected from leaching (other than in the special case of podzols); and there is a slow release of nutrients, in available forms, through mineralization. This release is to some extent synchronized with plant demands through the fact that litter decay is fastest at the onset of the rains; the capacity to control the timing of pruning and litter addition leads to a potential in agroforestry to regulate nutrient release so as to further synchronize it with plant requirements.

Other favourable consequences of organic matter upon nutrient supply are the blocking of phosphorus-fixation sites by organic complexes and the complexing and improved availability of micronutrients. It has also been suggested that a good organic matter status provides a favourable soil environment for nitrogen fixation.

A limit to the capacity of organic residues to supply nutrients should be emphasized, namely that what is not there in the first place cannot be recycled. If the soil parent material is low in phosphorus or potassium, then, however closed may be the soil-plant system, it cannot become richer in these elements without external inputs.

A further chemical effect is the considerable enhancement of cation-exchange capacity (CEC) by the clay-humus complex; this is particularly important where the CEC of the clay minerals is low, as in soils dominated by kaolinitic clay minerals and free iron oxides, such as ferralsols and acrisols. Raising the CEC improves nutrient retention, both of naturally recycled elements and of those added in fertilizers. A better response to fertilizers of soils with good organic-matter status has frequently been observed.

Soil humus also exerts a buffering action against acidity. Coupled with the fact that natural sources of nitrogen are non-acidifying, this offers a potential to check the problem of soil acidification.

Of the effects of organic matter on soil biological activity, the possible link to nitrogen fixation has been noted. Soil humus is the substrate for soil fauna, and whilst these are the primary cause of organic matter loss through oxidation, there are favourable effects, such as breakdown of pesticide residues. A list of 22 potential links between soil biological processes and management practices is given by Swift (1984, p. 17).

Two of the above aspects are primary themes in the Tropical Soil Biology and Fertility (TSBF) programme, the aim of which is to determine management options for improving tropical soil fertility through soil biological processes. The synchrony theme (SYNCH) aims to describe the mechanisms which determine the transfer of nutrients from decomposing organic matter to plant roots. This understanding should lead to a potential to synchronize the transfer through management practices. The soil organic matter theme (SOM) aims to determine the relationship between the organic and inorganic inputs to soil and the quality and quantity of soil organic matter formed, again with the intention of leading to an understanding of processes that will permit manipulation through management. The successive publications of this programme show a growing recognition that agroforestry provides some of the major practical management options to improving fertility through soil biological processes (Swift, 1984, 1985, 1987, in press).

The nature of soil organic matter

General

Soil organic matter is highly complex and its nature is the subject of specialized studies, far removed from the normal run of agroforestry research. An account of some aspects is given here for two reasons. First, those conducting studies of the effects of agroforestry systems upon soils should be aware that soil organic matter is not a single, homogenous, entity. Secondly, trees differ from crops in providing woody as well as herbaceous residues, and it may prove to be the case that woody material makes some distinctive contribution to soil organic matter. A working hypothesis for agroforestry research is suggested at the end of this section.

Fractions of organic matter

In terms of its physical state, the organic material present in a soil consists of two parts, plant remains and fully decomposed organic matter or humus. When a soil is prepared for analysis the larger fragments of plant litter and roots are normally removed, the litter by scraping it off the surface prior to sampling, the roots by retention on the 2 mm sieve during pre-treatment. However, plant fragments that are finely broken up but only partly decomposed remain. This has been called the light fraction of organic matter, since it can be separated by ultrasonic dispersion and flotation (density <2.0). Of the plant nutrient reserve stored in the soil, up to 25% may be in the light fraction (Ford and Greenland. 1968; Ford et al., 1969).

Early work on the soil organic-matter cycle was based on the two components, litter and humus (where 'litter' includes root residues). In the process of conversion from litter to humus, through the agency of soil fauna, there is a loss of carbon through microbial oxidation. The magnitude of such loss is one of the biggest unknown factors in the carbon cycle. Nye and Greenland (1960) suggested that between 10 and 20% of litter carbon was transformed into soil humus, and between 20 and 50% of root residues. This will be referred to as the *litter-to-humus conversion loss,* i.e. 80–90% for above-ground plant residues and 50-80% for roots.

After transformation to humus, a continuing loss of carbon takes place, again by microbial oxidation. The fundamental concept is that the amount of carbon so lost is proportional to that initially present, the rationale being that the population size of the organisms responsible depends on the substrate on which they feed, namely organic material. The proportion of soil humus carbon lost by oxidation during one year is the *humus decomposition constant.* From calculations based on carbon changes and equilibrium levels under shifting cultivation, Nye and Greenland estimated the decomposition constant under forest fallow (K_f) as 0.03, and under the greater soil disturbance of the cultivation period (K_c) as 0.04 (as percentages, 3 and 4% respectively). The equation underlying this concept is of the form:

$$C_t = C_0 - KC_0$$

$$\text{or } C_t = C_0(1 - K)$$

where C_0 = initial soil humus carbon, C_t = carbon after one year, and K is the decomposition constant.

These two parameters, conversion loss and decomposition constant, are the basis of the earlier approach to the soil organic-matter balance. Esti-

Table 17. *Estimates of the litter-to-humus conversion loss and the humus decomposition constant. Data are not fully comparable, owing to different assumptions made. Kf = under vegetation (fallow), Kc = under cultivation, Ka, Kb = different organic matter fractions, Kn = for release of nitrogen, r = see text.*

Country, environment	Litter-to-humus conversion loss in 1 yr (fraction)	Humus decomposition constant (fraction)	Source
West Africa			
forest	above ground: 0.75-0.9	Kf = 0.03 Kc = 0.033	Nye& Greenland (1960)
savanna	roots: 0.5-0.8	Kf = 0.008-0.009 Kc = 0.045	
Senegal			
savanna	0.5-0.9	Kf = 0.04-0.07	Charreau
woodland		Kc = 0.02-0.05	&Fauck(1970)
forest		Kf = 0.44, Kc = 0.06	Charreau (1975)
savanna		K = 0.02-0.09	
Nigeria			
savanna		Kc = 0.04-0.05	Jones & Wild (1975)
moist subhu mid		K = 0.07	Jenkinson & Ayanaba(1977)
Costa Rica	0.65	K = 0.13	Sauerbeck & Gonzalez (1977)
UK temperate		Ka = 0.014 Kb = 0.00035	Jenkinson & Rayner(1977)
Costa Rica	0.64-0.77	r = 0.12-0.23	Gonzalez & Sauerbeck(1982)
Queensland		Ka = 0.153-0.371 Kb = 0.022-0.0036	Dalai (1982)
South Austral ia	0.7		Ladd & Amato (1985)
Thailand		K = 0.077-0.088	Kyumaetal. (1985)
UK temperate		Kn = 0.028	Lathwell& Bouldin(1981) from sources quoted
USA temperate		Kn = 0.024-0.063	
Zaire		Kn = 0.330	
Assam, India		Kn = 0.099	
Puerto Rico		Kn = 0.224	

mates of their value are given in Table 17. Subject to reservations, this approach is still valid, and remains the basis for much applied research.

New light was cast upon organic-matter decomposition by the technique of isotopic labelling. Plants grown in an atmosphere artificially enriched in carbon-14 acquire tissues carrying this isotope. The amount of carbon-14 present can be detected regardless of the physical state it is in. By adding this labelled plant material to soil, its subsequent history can be followed. The methods are described by Vose (1980).

This technique was first applied to soils in temperate environments and subsequently in the tropics. The main isotope-based studies and reviews drawn upon in the following account are as follows: Jenkinson (1977), Jenkinson and Ayanaba (1977), Jenkinson and Rayner (1977), Sauerbeck (1977, 1983), Sauerbeck and Gonzalez (1977), Schnitzer (1977), IAEA (1977), Paul and Van Veen (1978), Cerri et al. (1982), Gonzalez and Sauerbeck (1982), Van Faassen and Smilde (1985), Ladd and Amato (1985).

Where carbon-14-enriched plant residues are added to soils, there is a decay curve of the same form both in temperate and tropical soils. This shows a rapid loss over the first 3 to 6 months, changing fairly abruptly to a slower and exponential rate of loss (Figure 8). A comparative study in a temperate climate (Rothamsted, Britain) and a moist subhumid tropical climate (Ibadan, Nigeria) showed that the two curves could be superimposed almost exactly if the time scale for Nigeria was divided by four. Subsequently, work in South Australia, under intermediate climatic conditions, produced a decomposition rate half that at Ibadan. In Costa Rica, under a humid tropical environment, the rate was similar to the Nigerian study. This last study was conducted on a variety of soils with the aim of showing how it varied with soil properties; contrary to expectations, the differences were relatively small and displayed no clear relations.

Curves for exponential decay of carbon are of the form:

$$\mathbf{C_t = C_0e^{-rt}}$$

where C, = carbon after time t (years), e is the exponential constant, and r is a parameter which describes the rate. For periods of a year and slow rates of decay (K and r < 0.1), the two preceding equations are nearly equivalent and K is nearly equal to r. The half-life of soil humus carbon, HL (years), is given by:

$$HL = 0.693/r$$

where 0.693 is the natural logarithm of 2.

Where there is a two-part curve, as in Figure 8, the equation for decay becomes:

$$C_t = d\text{-}e^{-rt} + C_2\text{-}e^{-r4}$$

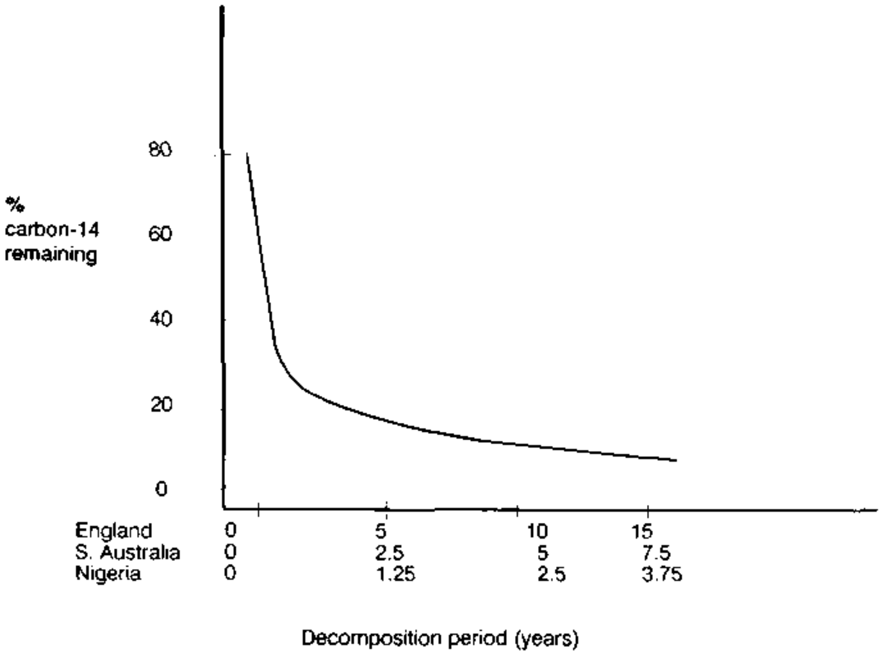


Figure 8. Decay curves for loss of carbon-14 labelled plant residues added to soil (after Ladd and Amato. 1985).

where C_1 and C_2 are the faster- and slower-decaying fractions of carbon, and r_1 and r_2 the corresponding values of r. In Gonzalez and Sauerbeck's (1982) results for Costa Rica soils, C_1 ranged from 52 to 72% of total carbon and C_2 correspondingly from 28 to 48%. Values of r_1 were mainly in the range 3.4-7.4; those of r_2 in the range of 0.12-0.23. Jenkinson and Ayanaba's (1977) values for Nigeria are similar.

Three lines of evidence suggest the existence of a third organic-matter fraction with a considerably slower rate of decay. First, there has for long been the anomaly that radiocarbon dating of soil organic matter has sometimes yielded values of hundreds of years. Secondly, given values of r_1 and r_2, it is possible to calculate the expected equilibrium value of soil carbon, which is about 1.5 to 3.0 times the annual addition of plant litter; observed values, however, are very much higher, which leads to the presumption that a third fraction with a substantially slower rate of decay must exist. The third line of evidence comes from the decay of non-labelled carbon in the same experiments, that is, carbon already present in the soil at the start of the labelling experiment. This is lost much more slowly than the labelled carbon, at about 3% per year, the value which in earlier work was taken for the decomposition constant. This unlabelled carbon is assumed to comprise a mixture of recently added and older material; to obtain the difference in rates between labelled (all recently added) and non-labelled carbon, some of the older material must have a considerably slower rate of decay.

Combining these two approaches, it seems likely that the 'conversion loss' in earlier work is equivalent to the fast-decay material in carbon-14 studies. That is, the organic material that is lost in six months or less consists of comminuted but not fully decomposed plant litter, which has not reached the stage of humus. This indicates the existence of at least three fractions of soil organic matter, of which only the second and third are humus:

- non-humified plant residues, with a half-life in tropical soils of less than six months; this may alternatively be treated as the litter-to-humus conversion loss;
- *labile humus* with a half-life in tropical soils of the order of three years;
- *stable humus,* capable of remaining in the soil for periods in excess of 50 years.

The non-humified material and the labile humus are likely to be the main contributors to nutrient release. It has been speculated that the stable humus contributes particularly to maintenance of soil physical properties, but there is evidence neither for nor against this.

Proposals that have been made for the nature of the various fractions of plant litter and soil organic matter are shown in Table 18. The first two rows refer to non-humified material, the third to carbon during passage through soil fauna, and the remainder to humus.

Implications for agroforestry: specialized research

The orthodox view is that the slow-decay, stable fraction of humus originates from microbial transformation of the labile fraction, as metabolites. The maintenance of the stable fraction would then be dependent on a continuing supply of labile material, and degradation of the latter would result in a delayed and slower decline of the stable material.

An alternative possibility is that lignin-rich plant residues contribute directly to, or at least favour, the formation of the stable humus fraction. If this were so, then there is a management implication for agroforestry, namely that where possible, twigs and fine branches should be left to rot with leaf litter, and not removed for convenience of agricultural operations.

A more general hypothesis, originating from the Tropical Soil Biology and Fertility programme, is that plant litter of differing quality contributes differentially to the properties and maintenance of soil humus (Swift, 1987, pp. 34-41; in press). This is clearly the case with respect to rates of litter decay and consequent release of nutrients prior to humification. What is

Table 18. *Fractions of plant litter and soil organic matter. Fractions given in the same rows are not necessarily equivalent.*

Jenkinson and Rayner(1977)	Rosswall (1984)	Coleman (1985) Partonetal.(1987)
Decomposable plant material	Labile plant litter	Metabolic plant carbon
Resistant plant material	Refractory plant litter	Structural plant carbon
Soil biomass	Microbial biomass, necromass and metabolites	Active soil carbon (microbial)
Physically stabilized humus	Stabilized organic matter	Slow soil carbon
Chemically stabilized humus	Old organic matter	Passive soil carbon

not known is whether a difference between retaining or removing woody residues has implications for the nature and maintenance of soil humus. Soil physical conditions are particularly favourable under natural forest ecosystems, where there is a balanced supply of herbaceous and woody residues. The potential of agroforestry to supply both kinds of residue is a point in its favour, in very general terms. A long-term experiment based on supplying soil plots with herbaceous residues only, woody residues only, and a mixture could shed light on this question.

Much of the above is a matter for soils research by institutions with special skills and facilities. Isotope-based work is conducted through a network linked to the Joint FAO/IAEA (International Atomic Energy Agency) Division in Vienna, Austria, which has recently included agroforestry among its interests (IAEA, in press; Young, in press, c). Advances in knowledge in these specialized fields are of considerable potential significance to agroforestry.

A working hypothesis for soil monitoring in general agroforestry research

Most stations carrying out agroforestry research will neither wish, nor have the facilities, to carry out such specialized work. However, the monitoring of soil changes should form a part of most agroforestry experimental work, both tree/crop interface studies and trials of systems. For such studies a working hypothesis is needed that, whilst not ignoring the complexities of the subject, permits useful results to be obtained from standard methods of sampling and analysis.

We know very little about the stable humus fraction, other than that it exists; it forms part of the organic carbon given by the standard (Walkely-Black) method of analysis, and the organic matter given by the method of ignition at 375°C. Its rate of oxidation loss is unknown, and it is affected by management, if at all, only slowly. What is of interest, for research into practical methods of soil fertility maintenance, is the labile fraction, which can be increased or reduced over periods of a few years by the supply of plant residues.

The humification of plant litter takes place at the soil surface or in the topsoil, the uppermost 15 to 30 cm where organic matter dominates the soil colour. This is where most soil biological activity (other than termites) is concentrated. It is reasonable to suppose that much of the humus present in the organic-rich topsoil horizon is in labile form; and conversely, that the humus in the lower soil horizons, which does not prevail over the red to yellow colours of iron oxides, contains a proportionally greater amount of stable humus.

The simplification suggested as a matter of practical convenience is to treat *all* fully humified carbon in the dark-coloured topsoil horizon as belonging to the labile fraction, with a decomposition constant of the order of 3-10%; and to focus attention mainly, although not exclusively, on soil organic matter changes in this horizon. The monitoring, perhaps at intervals of several years, of corresponding changes in lower horizons should allow approximate relations with topsoil changes to be established.

The organic-matter cycle

Introduction

Under natural vegetation, the soil organic-matter level is improved or maintained; under rainfed arable agriculture, it declines. The tree component in agroforestry has a capacity for biomass production at least as great as that of natural vegetation. The basic hypothesis to be considered is that it is possible to design agrosylvicultural systems in which the organic matter loss under the crop component is matched by a gain under the tree component. To be of practical use, such systems must also fulfil the needs of the land users for food crops and other products.

One basis is the studies by ecologists of the plant/soil organic-matter cycle under natural vegetation. A second is the experimental work on soil changes under continuous cropping or short fallows, much of it conducted with the aim of finding alternatives to shifting cultivation. These provide data which can be applied to the fundamental situation in agrosylvicultural systems, that of tree and crop components combined in space or time.

The cycle is discussed in terms of organic carbon, assumed to make up half of dry-matter plant material and 58% of soil organic matter. Data are given as kilogrammes per hectare or kilogrammes per hectare per year.

The cycle under natural vegetation

The foundation for modelling of organic matter cycling was provided by the classic study of Nye and Greenland (I960); this section is largely based on the analysis of their data given in Young (1976). Other outstanding studies of natural vegetation are those of lowland rainforest by Bernhard-Reversat (1977), Bernhard-Reversat et al. (1975), Golley et al. (1975) and Jordan (1982); of highland forest by Lundgren (1978); and of both forest and savannas by Lelong et al. (1984). These later studies have confirmed the orders of magnitude for stores and flows of carbon established by Nye and Greenland.

Representative values for stores and flows of carbon for two ecological zones, humid and moist subhumid, are shown in Figure 9. The savanna data are subdivided according to whether it is burnt (with assumed loss of above-ground vegetation) or unburnt. The losses of carbon from the soil humus, through bacterial oxidation, are based on the concept of the decomposition constant. Its value under forest, K_f. is taken as 3% (0.03) and under cultivation, K_c, as 4%. The assumption of a decomposition constant provides a homeostatic mechanism whereby soil organic matter will tend towards an equilibrium value under constant inputs, however large or small these may be. This model takes no account of the existence of varying qualities of soil organic matter, with differing rates of breakdown.

Figure 9 gives the cycles for the rainforest and moist savanna conditions, showing the position under equilibrium conditions. Gains to soil humus equal losses, at 1900 kg/ha/yr in the forest environment and 1200 kg/ha/yr under savanna. The soil humus contents of 63 300 and 57 000 kg/ha/yr carbon respectively are equivalent, making a number of assumptions, to topsoil organic matter levels of 4.2% under forest and 3.8% under savanna.

The cycle under agriculture: continuous cropping

As a basis for discussing carbon flows under agriculture, one of these environments only is selected, that of rain forest. A cereal crop is assumed (typically maize), with a grain yield of 3000 kg/ha, representative of intermediate inputs or improved farming. Two alternatives considered are that the crop residues are or are not returned to the soil. It is assumed that cultivation has already lowered soil humus to half its level under forest, 35 000 kg/ha carbon. The harvest index (grain as percent of above-ground biomass) is taken as 33%, and biomass of roots as 33% of the above-ground biomass. The same assumptions are made as in Figure 9, namely that the

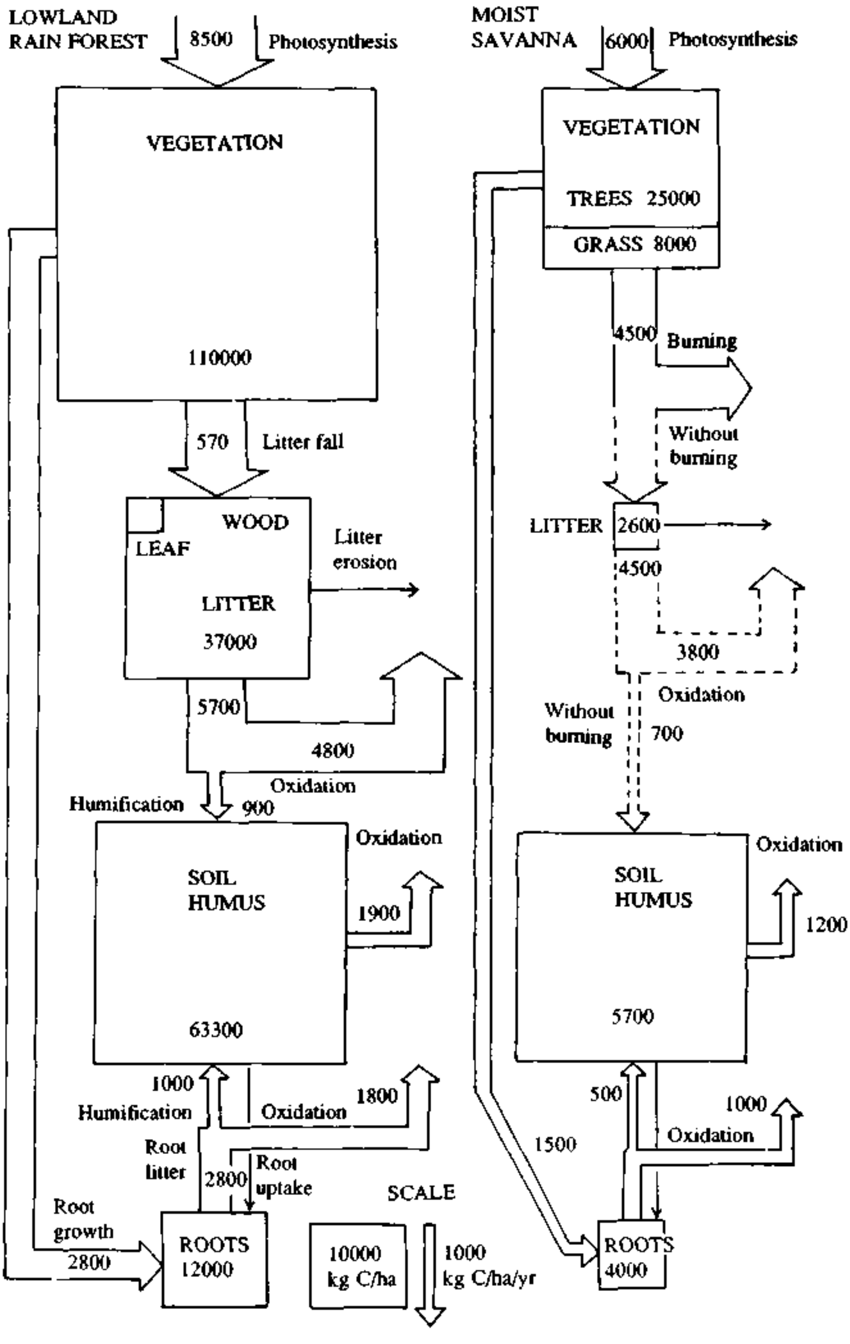


Figure 9. The earbon cycle under natural vegetation (after Young, 1976. p. 111. based mainly on data in Nye and Greenland, 196(1).

split between humification and oxidation loss is 15:85 for crop residues and 33:67 for roots.

There is a net loss of soil carbon amounting to 2.5% of its initial value with crop residues removed and 1.2% where they are retained. The cycle with residues removed is shown in Figure 10. Under continuous cereal cropping, the soil is being degraded at a substantial rate. This would reduce crop growth, so lowering the additions of plant residues and accelerating the loss. Equilibrium is eventually reached but at an unacceptably low level of crop production and with severely degraded soil properties. Such a feedback between soil conditions and plant growth, leading to an accelerating rate of soil degradation and crop yield decline, can be demonstrated by the SCUAF (Soil Changes Under Agroforestry) computer model described in Chapter 15.

The cycle under a spatial agroforestry system

Taking the same data as in the above accounts of natural vegetation and continuous cropping, it is possible to construct a first approximation of the cycling of organic matter (represented by carbon) under a schematic agroforestry system. The model is based on the following assumptions:

- a humid tropical climate;
- an initial soil organic level of about 60% of that typical for a medium-textured soil in this environment;
- the planting of trees which have a rate of growth, and thus litter production, equal to that of a natural forest fallow;
- the assumptions of a 'moderate' crop yield (3000 kg/ha grain) with crop residues removed;
- an agrosylvicultural system in which trees and crops each occupy 50% of the land.

This schematic cycle is applicable either to a spatial-mixed agroforestry system or to a spatial-zoned system in which, by one means or another, inputs and outputs of carbon become evenly distributed in space over a period of years. The effects are similar for a rotational tree/crop system, except that the curve of soil carbon against time has a toothed pattern.

The carbon cycle is shown in Figure 11. Inputs from tree and crop components are unchanged, but the assumption of the decomposition constant leads to approximate halving of the oxidation losses. Under the crop component there is still a net annual loss of 860 kg/ha carbon, but this is balanced by an equal net gain under the tree component. The agroforestry system as a whole—soil, soil organisms, tree, crop and environment—is stable.

The assumption of a 50:50 ratio between the tree and crop components is plausible for a spatial-mixed system but not for most spatial-zoned systems. However, this might be compensated by the higher rates of growth

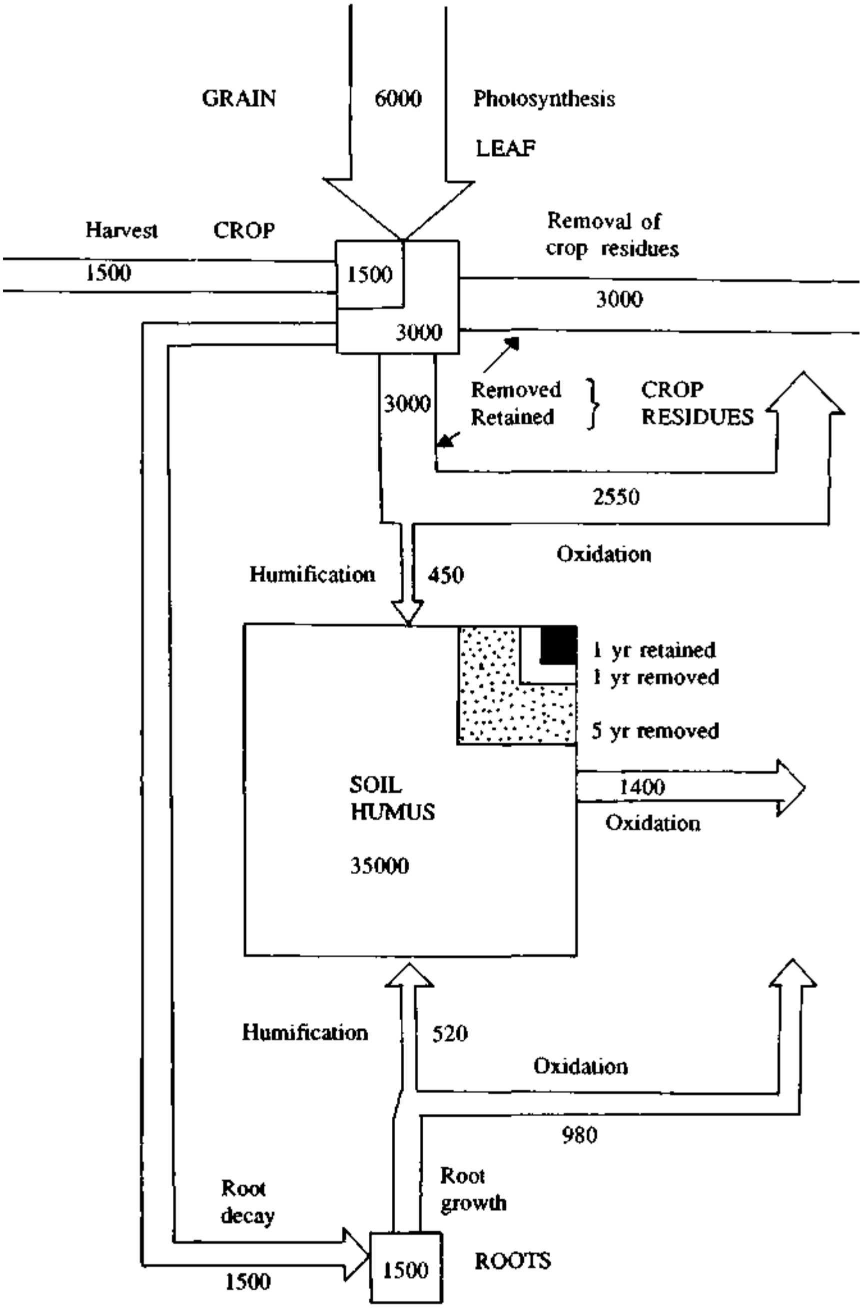


Figure 10. The carbon cycle under a cereal crop, lowland humid zone, crop yield 3000 kg/ha. Values are kg C/ha and kg C/ha/yr. Shaded areas show net losses of soil carbon.

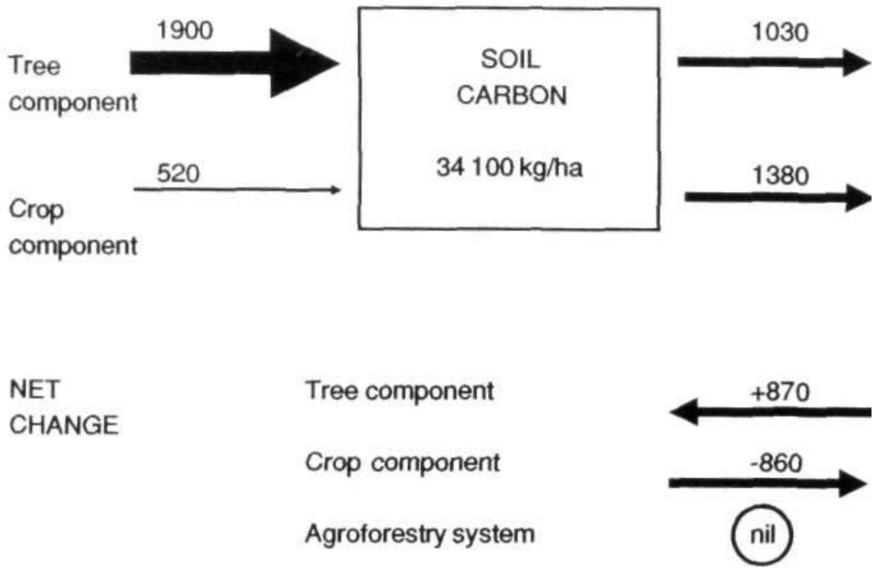


Figure 11. Changes in soil carbon under agroforestry. Data and assumptions are the same as for Figures 9 and 10.

obtainable from the managed tree component in spatial systems. Thus, the equivalent result to the above would be obtained from a hedgerow intercropping system with 25% tree cover having a growth rate twice that of natural vegetation.

This result is exciting in the prospects which it opens up. It amounts to an hypothesis that, provided the assumptions can be verified, agroforestry systems can be designed that are productive in terms of agricultural crops, and at the same time lead to a steady state of soil organic matter.

Trees as **producers of biomass**

Natural vegetation

Measured rates of net primary production under natural ecosystems serve as a reference point for agroforestry in two ways. First, they indicate the relative biological productivity to be expected under different climates. Secondly, they would provide minimum values to be expected, if it could be assumed that under agroforestry the combined effects of species selection and management will achieve higher rates of biomass production.

A summary of ranges and mean values is given in Table 19, the sources for which are compilations from primary data. The most representative value for rain forest is 20 000 kg/ha/yr (dry matter), ranging from half to over twice this value; semi-deciduous forest, under climates with a short

Table 19. *Biomass production of natural vegetation. Values refer to above-ground dry matter (kglhaiyr). The sources are reviews, with substantial communality in primary data sources.*

Vegetation community	Equivalent climate (Koppen)	NPP (kgDM/ha/yr) Range	Mean or typical	Source
Evergreen rain forest	Af	10 000-35 000	28 000	Leith(1976)
			23 000	Leith& Whittakcr (1975)
			23 000	Murphv(1975)
		22 000-32 000		UNESCO (1978)
		10 000-50 000	20 000	Whittaker& Woodwell (1971)
			33 000	Rodin & Basilevic (1968)
Semi-deciduous rain forest	Am	16 000-25 000	17 500	Leith(1976)
			18 000	Leith& Whittakcr (1975)
		13 000-17 000		UNESCO (1978)
			21 000	Murphy (1975)
Montane ('cloud') rain forest	Cf,Cm		22 000	Leith& Whittakcr (1976)
Savanna	Aw	2000-29 000	8000	Leith(1976)
			9000	Leith& Whittaker (1975)
		2000-20 000	7000	Whittaker & Woodwell (1971)
Moist savanna	Aw	5000-15 000	10 000	Murphy (1975)
			7000	Rodin and Basilevic (1968)
Dry savanna	Aw	3000-8000	5000	Murphy (1975)
			7000	Rodin and Basilevic (1968)
Semi-desert vegetation	BS	100-2500	700	Lcith(1976)
			2000	Rodin and Basilevic (1968)

dry season, is only slightly lower than evergreen forest in typical value, but docs not attain the very high rates of some evergreen sites. Forest at high altitudes does not necessarily have slower growth; the typical value shown, 22 000 kg/ha/yr, is almost identical to that subsequently measured in Tanzania by Lundgren (1978).

Savanna communities show a wide range of productivity, differing between moist savanna, dominated by broadleaf species and occurring above some 1000 mm/yr rainfall, and dry savanna, dominated by narrow-leaved species. Representative values are 10 000 kg/ha/yr for moist savanna and 5000 for dry savanna. Communities described as desert scrub or the like range downwards from 2500 kg/ha/yr.

In summary, studies of natural ecosystems suggest the following rates of net primary production (above-ground dry matter) that can be expected according to climatic zone:

Humid tropics (no dry season)	20 000 kg/ha/yr or more
Humid tropics (short dry season)	20 000 kg/ha/yr
Subhumid tropics (moist)	10 000 kg/ha/yr
Subhumid tropics (dry)	5000 kg/ha/yr
Semi-arid zone	2500 kg/ha/yr or less.

Biomass production by trees used in agroforestry

Table 20A gives examples of measured biomass production by multipurpose trees, either grown in agroforestry systems or as plantations. These results are fragmentary, and will be considerably augmented in a few years by data from trials recently started.

Most of the rates shown do not exceed the baseline figures for natural vegetation under corresponding climates given above. Exceptions are two genera that have been the subject of breeding-improvement programmes, *Leucaena* and *Prosopis.* Most other data range from net primary production rates typical of natural vegetation to half such values.

The data refer to biomass production from the tree component in practical systems; for the Nigerian data, tree rows are spaced 4 m apart, and thus occupy perhaps 25% of the total ground area. If the crop net primary production of about 10 000 kg/ha/yr (from two crops) is added, the total biomass production of the system reaches some 15 000 kg/ha/yr. The site (at IITA, Ibadan) is close to the margin between moist subhumid and humid climates, so this rate is about what might be expected from natural ecosystems.

For a spatial-mixed system, there are several studies of the plantation-crop combinations common in Central and South America. In these, coffee or cocoa are interplanted with *Cordia alliodora* and/or *Erythrina poeppigiania.*

Table 20. *Biomass production of multipurpose trees.*
A: Above-ground net primary production (kgDMIhalyr).

Climate, Country	Land use	Tree	NPP	Source
Humid				
Malaysia	Plantation	*Acacia mangium*	18 000	Lim(1985)
Sarawak	Plantation	*Acacia mangium*	15 500-18 300	Tsai & Hazah (1985)
Philippines	Plantation	*Albizia falcataria*	11 300	Kawahara etal.(1981)
Costa Rica	Hedgerow intercropping	*Calliandra calothyrsus*	4390	Baggio & Heuveldorp (1984)
Colombia	Plantation crop combination	Coffee+shade trees	4600-13 000	Bornemisza (1982)
Mexico	Plantation crop combination	Coffee, *Inga spp.*	8400-9500	Jimenez & Martinez (1979)
Mexico	Plantation crop combination	Coffee, *Inga spp.*, banana	10 250	Jimenez & Martinez (1979)
Costa Rica	Plantation crop combination	*Erythrina poeppigiana*	13 700-22 700	Russo & Budowski (1986)
Costa Rica	Plantation crop combination	*Cordia alliodora*	9720	Alpizaret (1986,1988)
		C. alliodora + cacao	16 360	
		Erythrina poeppigiana	8710	
		E. poeppigiana +cacao	15 740	
Philippines	Plantation	*Gmelina arborea*	12 700	Kawahara etal. (1981)
Hawaii, etc.	Plantation	*Leucaena leucocephala*	20 000-30 000	Pound & Cairo 1983
Various	Plantation	*Leucaena leucocephala*	40 000-80 000	Brewbaker (1987)
Moist subhumid bimodal				
Nigeria	Hedgerow intercropping	*Cassia siamea*	7390	Yamoah et al. (1986b)
Nigeria	Hedgerow intercropping	*Flemingia congesta*	2370	Yamoah et al. (1986b)
Nigeria	Hedgerow intercropping	*Gliricidia sepium*	4770	Sumberg (1986)
Nigeria	Hedgerow intercropping	*Gliricidia sepium*	5410	Yamoah et al. (1986b)
Nigeria	Hedgerow intercropping	*Gliricidia sepium*	3000-4500	Bahiru Duguma et al.(1988)
Nigeria	Hedgerow intercropping	*Leucaena leucocephala*	6770	Kanget al. (1985)

Table 20 (cunt)

Climate. Country	Land use	Tree	NPP	Source
Nigeria	Hedgerow intercropping	*Leucaena leucocephala*	8000-16 000	Bahiru Duguma et al. (1988)
Nigeria	Hedgerow intercropping	*Sesbania grandiflora*	1000-3500	Bahiru Duguma et al. (1988)
Subhumid bimodal				
Sri Lanka	Hedgerow intercropping	*Leucaena leucocephala*	2800	Weerakoon (1983)
Subhumid				
India	Plantation	*Leucaena leucocephala*	38 200	Mishra et al. (1986)
Various	Plantation	*Leucaena leucocephala*	10 000-25 000	Pound & Cairo (1983)
Range	Plantation	*Leucaena leucocephala*	20 000-50 000	Brewbakcr (1987)
Dry subhumid				
India	Plantation	*Prosopis juliflora*	30 000	Gurumurti etal.(1984)
Arid				
USA	Woodland	*Prosopis glandulosa*	3700	Rundel et al. (1982)
Arid, with groundwater				
California (USA)	Natural woodland	*Prosopis glandulosa*	4000	Virginia (1986)
Arid, irrigated				
USA	Plantation	Four *Prosopis* spp.	7000-14 500	Felkeret al. (1983)
Various				
Nigeria/ Brazil	Plantation	*Gmelina arborea*	9300-24 900	Chijoke (1980)

The *CordialErythrina* component alone typically supplies some 10 000 kg/ha/yr of biomass. In these systems the crop component is also a woody perennial, and if its biomass is added the total reaches some 15 000 kg/hr/yr.

Table 20B shows corresponding production of leaf (herbaceous) material only. Biomass is considerably lower, of the order of 2000-4000 kg/ha/yr for humid and subhumid climates. Values for leaf fodder production assembled in the ICRAF multipurpose tree and shrub data base are even lower, mostly a few hundred kilogrammes per hectare per year (von Carlowitz, 1986b, p. 311).

The partitioning of dry-matter production between the four plant components, leaf (herbaceous), reproductive (fruit and flower), wood and root

Table 20. *Biomass production of multipurpose trees.*
B: Leaf production (kgDMIhalyr).

Climate, Country	Land use	Tree	NPP	Source
Humid				
Malaysia	Plantation	*Acacia mangium*	3060	Lim(1985)
Philippines	Plantation	*Albizia falcataria*	180	Kawahara etal.(1981)
Costa Rica	Hedgerow intercropping	*Calliandra calothyrsus*	2760	Baggio& Heuveldorp (1984)
Philippines	Plantation	*Gmelina arborea*	140	Kawahara etal.(1981)
Java	Plantation	*L. leucocephala, A. falcataria Dalbergia latifolia Acacia auriculiformis*	3000-5000	Buck (1986)
Costa Rica	Plantation crop combination	*Cordia alliodora*	2690	Alpizar et al. (1986,1988)
		C. alliodora+cacao	6460	
		Erythrina poeppigiana	4270	
		E. poeppigiana +cacao	8180	
Moist subhumid bimodal				
Nigeria	Hedgerow intercropping	*Cajanus cajan*	4100	Agboola (1982)
Nigeria	Hedgerow intercropping	*Gliricidia sepium*	2300	Agboola (1982)
Nigeria	Hedgerow intercropping	*L. leucocephala*	2470	Agboola (1982)
Nigeria	Hedgerow intercropping	*Tephrosia Candida*	3070	Agboola (1982)
Subhumid				
India	Plantation	*L. leucocephala*	2300	Mishra etal.(1986)

is a matter of considerable importance to agroforestry, since some of these components will be harvested, others returned to the soil. It not only depends on tree species, but is affected by environment and management; for example, nutrient stress decreases shoot (above-ground) growth relative to root growth, removal of fruit increases vegetative growth, whilst repeated removal of vegetative parts (as in pruning) decreases future vegetative growth. A review of dry-matter partitioning in tree crops is given by Cannell (1985).

Besides tree species, climate and soil, the rate of growth can be affected by the pruning regime. At Ibadan, Nigeria, pruning frequencies of three, two and one months progressively reduced dry-matter yield as compared with six-monthly pruning; lower pruning heights had a smaller but still substantial effect (Bahiru Duguma et al., 1988). Thus the frequent prunings that are desirable to reduce shading may have an adverse effect on tree growth; finding a compromise is a matter for local adaptive research.

The estimated production of plant biomass, and proportion of this returned to the soil, must be estimated for any given site, agroforestry system, tree species and management. The above discussion can be summarized in general terms as follows:

1. The biomass production from the tree component in agroforestry systems can approach that under natural vegetation in the same climatic zone, and possibly exceed it for plant species which have been improved by selection or breeding.
2. For the provision of biomass to maintain soil organic matter, critical aspects are, first, the partitioning of biomass between different parts of the plant, and secondly, which of these plant parts reaches the soil as litter.

Plant-residue requirements to maintain soil organic matter

Table 21 is an attempt to estimate, in highly generalized terms, the plant residues that need to be added to the soil in order to maintain soil organic matter for three climatic zones of the tropics. The working hypothesis proposed above is assumed, to consider only topsoil carbon and assume that this all belongs to the labile fraction. Values are obtained as follows:

- *Initial topsoil carbon and topsoil carbon percent.* Representative values for topsoil organic matter for the zone, under agricultural or agroforestry use, at levels commonly regarded as acceptable to maintain soil physical conditions; divided by 1.72 to give carbon.
- *Oxidation loss.* Assuming a decomposition constant of 0.04.
- *Erosion loss.* This will vary with site conditions from almost nil to high values. The assumption made is that erosion has been reduced to what is commonly regarded as an achievable rate, 10 t/ha/yr of soil. This is multiplied by the topsoil carbon, and by a carbon enrichment factor in eroded sediment of 2.0.

Table 21. *Indicative plant biomass requirements for maintenance of soil organic matter.*

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 (kgDM/ha/yr) above ground	roots
Humid	30 000	2.0	1200	400	1600	8400	5800
Subhumid	15 000	1.0	600	200	800	4200	2900
Semi-arid	7500	0.5	300	100	400	2100	1400

- *Required addition to soil humus.* The sum of oxidation and erosion losses.
- *Required plant residues added to the soil.* It is first assumed that roots equal 40% of above-ground net primary production. The conversion loss is taken as 85% for above-ground residues and 67% for roots. Plant dry matter is assumed to be 50% carbon, and the results rounded to the nearest 100.

Since the roots are almost invariably added to the soil, the results can be treated in terms of above-ground biomass. To maintain organic matter, a land-use system in the humid tropics should add something of the order of 8000 kg DM/ha/yr to the soil. Corresponding values for the subhumid and semi-arid zones are 4000 and 2000 kg DM/ha/yr.

Comparison with Table 20 shows that these requirements can certainly be met if the total tree biomass is added to the soil, and still more readily if herbaceous crop residues are also added. If the woody component of the tree is harvested, achievement of the requirement becomes more difficult, and it is impossible if tree foliage and crop residues are also removed. The balance between additions and losses of soil humus carbon can be estimated for any given system, within a specified environment, by similar calculations; the computer model, SCUAF, described in Chapter 15, is an aid to the exploration of alternative possibilities.

Litter quality and decomposition

So long as the nutrients contained in plant litter are held as organic molecules, they are protected from leaching. When the litter decomposes, these nutrients are released to the soil solution. They then become available for uptake by plant roots, but at the same time, become subject to loss from the plant-soil system through leaching.

The concept of the *quality* of plant residues refers to their relative content of sugars, cellulose, hemicellulose, lignin and phenols, and the proportional content of nutrients. Litter of high quality (high in nutrients, low in lignin) decays and releases nutrients rapidly, that of low quality (high in lignin and/or phenols) decays slowly (Swift et al., 1978). Woody residues (stems,

QUALITY OF PLANT RESIDUES

- High-quality residues: high in nitrogen, low in lignin and polyphenols; decay rapidly, giving short-term release of nutrients to meet peaks in plant requirements.
- Low-quality residues: low in nitrogen, high in lignin and/or polyphenols; decay slowly, giving extended release of nutrients, protected against leaching until mineralized.

branches and twigs, coarse roots) are of low quality, but so also are some herbaceous products including straw.

It is apparent that the trees used in agroforestry vary widely in their quality and rates of decomposition. Leaves of *Leucaena* disappear within a few weeks, those of *Cassia siamea* at an intermediate rate, whilst *Gmelina arborea, Acacia mangium* and many *Eucalyptus* species are relatively slow decaying. For example, *Leucaena, Gliricidia* and *Cassia* prunings release most nitrogen within 60 days of application to the soil. *Leucaena* decomposes mainly within 40 days, more rapidly if applied fresh than dry, and if buried than applied to the surface. For the same climatic and soil conditions at Ibadan, Nigeria, the rate of decomposition of prunings is *Leucaena leucocephala* > *Gliricidia sepium* > *Cassia siamea* > *Flemingia congesta* (for cutbacks, or first prunings, the order of *Cassia* and *Flemingia* was reversed) (Yamoah et al., 1986a, 1986c; Wilson et al., 1986).

In Colombia, the half-life of litter was 60 days for *Albizia carbonaria,* 80 days for *Gliricidia sepium* and *Sesbania grandiflora,* 120 days for *Erythrina* sp. and *Cajanus cajan* and 170 days for *Cassia grandis.* The decomposition rate for all species was directly proportional to rainfall. For *Albizia, Sesbania* and *Gliricidia,* over 80% of nitrogen, phosphorus and potassium were released within 170 days (Arias, 1988). The straw from crop residues takes several months to become humified, and coarse woody residues longer still.

The rate of litter decomposition is expressed in terms of the *litter decomposition constant,* K_{lit} (commonly expressed as 'k' but here designated K_{lit} to distinguish it from the decomposition constant for soil humus). The rate of change in accumulated surface litter, dL/dt, is given by:

$$dL/dt = A - (K_{lit} \times L)$$

where A = annual litter additions and L = accumulated surface litter. If $K_{lit} < 1.0$, then the mean residence time of litter on the ground surface is less than one year. This is the case for most natural ecosystems in the tropics.

The decomposition constant for a given plant species on a site is relatively easily measured by the litter-bag technique (Anderson and Ingram, 1989). This should become a normal element in agroforestry research, leading to establishment of decomposition constants for common tree species within given environmental conditions, in particular with respect to the major climatic zones.

There are four management alternatives for litter: placement on the surface, burial in the soil, composting, or use as fodder with return of manure. Buried litter decomposes faster than surface litter (Wilson et al., 1986). Surface placement is desirable for erosion control, but preference for nutrient release depends on the interaction of climate, tree species and timing of plant demand. Composting is normal in the temperate zone, to avoid nitrogen starvation caused by the high C:N ratio of fresh plant material, but this does not appear to be a problem under the faster decomposition conditions of the tropics. Composting is common practice in some tropical countries (e.g. Rwanda) and has its staunch advocates (Dalzell et al., 1987). Most agroforestry systems, traditional and modern, at present use surface addition. Burial or composting may be more desirable for cereal crop residues, which are high in lignin, than for the generally high litter quality of tree leaves.

Knowledge of the rates of litter decomposition offers opportunities to manipulate the timing of nutrient release. Annual crops vary in their nutrient requirements during the growing season. It is therefore beneficial if the release of nutrients from litter decay can take place at the same time as uptake requirements of crops. In this way, the ratio between plant uptake and leaching loss will be increased, thereby making the plant-soil system more closed. The concept that nutrient release and requirements for uptake can be synchronized, to some degree, through management forms one of the basic hypotheses of the Tropical Soil Biology and Fertility programme (the synchrony or 'SYNCH' hypothesis) (Swift, 1984, 1985, 1987, in press).

This is one reason for the success of combinations of *Leucaena, Gliricidia, Flemingia* and *Cassia* with maize. Nitrogen release from prunings is well synchronized with nitrogen uptake by maize; if prunings are applied at time of germination, uptake surpasses release after 40 to 50 days (Yamoah et al., 1986a). For annual cropping systems, tree species with a high quality of leaf litter appear desirable, not only because of the higher nutrient content but also because its release synchronizes well with crop uptake requirements.

Agroforestry systems differ from natural plant communities, first, in that there is some degree of selection of plant species, and second, in that the tree and crop components are managed, e.g. by pruning and harvesting. Hence many agroforestry systems offer opportunities to manipulate the timing of litter decay and nutrient release. This can be achieved through:

1. selecting plant species with differing rates of litter decomposition;
2. manipulating the timing of litter addition to the soil, through adjustments in the timing of pruning or other tree-cutting operations;
3. controlling the manner of litter addition, i.e. left on the ground surface or buried.

Tree species selection is influenced by a variety of considerations, whilst the timing of pruning is often determined by the need to reduce shading to young crops. However, once basic knowledge on the timing of litter decomposition has become available, there will often be opportunity to modify one or more of the three features listed above so as to synchronize nutrient release with plant requirements, thereby increasing plant uptake relative to leaching loss and so achieving a more closed plant-soil nutrient cycle.

Chapter 10
Plant Nutrients

Because it is concerned with the cycling of plant material, agroforestry is necessarily concerned with the complete range of plant nutrients: the major nutrients, nitrogen, phosphorus and potassium; the secondary nutrients, calcium, magnesium and sulphur; and the trace elements or micronutrients, of which about seven are required for plant growth.

Nitrogen or phosphorus are most frequently the limiting nutrients in tropical soils. There is nearly always a substantial initial response to nitrogen fertilizer application. Phosphorus deficiency commonly appears after a few years of cultivation, when initial soil supplies become depleted. Potassium is less commonly limiting, except under root crops. Sulphur deficiency appears locally, where it is deficient in soil parent material.

Deficiencies in micronutrients are most likely to appear where major nutrient shortages are remedied by fertilizers. In this respect, biological means of soil improvement have an inbuilt advantage, in that plant residues are likely to contain the small quantities of elements required. This could be a significant benefit from agroforestry.

There is a fundamental distinction in kind between nitrogen, originating from atmospheric fixation, and the other nutrients, the original source of which is rock weathering. By means of biological nitrogen fixation one can, as it were, get 'something for nothing'; and by combining fixation with efficient recycling, self-sustaining yet productive ecosystems can be devised. But since nutrients are necessarily removed in harvest, they must be replaced, and if not present in soil parent materials, no amount of recycling can make up what is not there. If nutrient reserves are present in weathering rock but only at depth, tree roots may be able to tap sources unavailable to crops. There is a second source in atmospheric deposition, in rain and dust, which may be substantial in relation to the low requirements of natural vegetation but is small in comparison with rates of removal in harvest.

Thus in general, land-use systems with no artificial inputs can only be sustainable at low levels of output. It would be mistaken, however, to consider agroforestry as a means of maintaining fertility solely through biological means. Its potential would be greater if it could also be shown to increase the efficiency of use of fertilizers.

Nitrogen fixation by trees and shrubs

Biological nitrogen fixation takes place through non-symbiotic and symbiotic means. Non-symbiotic fixation is that carried out by free-living soil organisms. It can be of substantial importance relative to the modest requirements of natural ecosystems, but is small in relation to the greater demands of agricultural systems. Presumably it varies with the organic-matter status, and therefore microbiological activity, of the soil.

Symbiotic fixation occurs through the association of plant roots with nitrogen-fixing bacteria. Many legumes are associated with *Rhizobium*, whilst a few non-leguminous species are associated with *Frankia.* These symbioses occur in association with soil fungi which infect roots to form mycorrhizae (von Carlowitz, 1986a, p. 243).

Nitrogen fixation by herbaceous legumes has long been a recognized agricultural practice, either as a productive crop (e.g. pulses, groundnuts), a green manure crop (e.g. Stylosanthes spp., *Centrosema pubescens)* including grass-legume leys, or a cover crop in perennial plantations (e.g. *Pueraria phaseoloides).* Typical rates of nitrogen fixation for herbaceous legumes are in the range 40-200 kg N/ha/yr (Nutman, 1976; LaRue and Patterson, 1981; Gibson et al., 1982).

Table 22 gives reported rates of nitrogen fixation by trees and shrubs. These are very approximate, as there are problems in all the three methods of measurement: nitrogen difference, acetylene reduction and 15-N labelling (Dommergues, 1987, p. 262). Use of 15-N labelling permits estimates of the proportion of plant tissue nitrogen derived by fixation, e.g. 34-39% in *Leucaena* at Ibadan, Nigeria, and 60% in *Prosopis glandulosa* in California (Sanginga et al., 1987; Virginia, 1986).

Cassia siamea is intriguing: it is believed not to be nitrogen fixing yet holds large amounts of nitrogen in its foliage and appears capable of improving soil nitrogen. Most data in the table refer to trees in pure stand, but those for coffee with *Inga* and hedgerow intercropping with *Leuceana* are for cultivation in spatial-mixed and zoned agroforestry systems respectively. The range is largely 20-200 kg N/ha/yr, with *Leucaena* alone capable of higher values under favourable climatic and soil conditions. There is a need for more data, but it is at least a plausible hypothesis that trees and shrubs can be identified which, grown in agroforestry systems, will be capable of fixing of the order of 50-100 kg N/ha/yr.

The use of nitrogen-fixing trees can reduce root competition with crops. Nitrogen is a relatively mobile nutrient. If the tree obtains its supplies partly by fixation this reduces the soil depletion around its roots, so allowing more nitrogen to be taken up by interplanted non-nitrogen-fixing crops (Gillespie, in press).

Sources for the selection of nitrogen-fixing trees and shrubs are the data base of the Nitrogen-Fixing Tree Association (NFTA) (Halliday, 1984)

Table 22. *Nitrogen fixation by trees and shrubs. Nair (1984) and Dommergues (1987) are compilations from primary sources.*

Species	N fixation (kgN/ha/yr)	Source
Acacia albida	20	Nair (1984)
Acacia mearnsii	200	Dommergues (1987)
A llocasuarina littoralis	220 (?)	Dommergues (1987)
Casuarinaequisetifolia	60-110	Dommergues (1987)
Coffee + *Inga* spp.	35	Roskoski & van Kessel (1985)
Coriaria arhorea	190	Dommergues (1987)
Ery th rina p oepp igian a	60	Dommergues (1987)
Gliricidia sepiurn	13	Dommergues (1987)
Inga jinicuil	35-40	Dommergues (1987)
Inga jinicuil	50	Roskoski (1982)
Inga jinicuil	35	Roskoski & van Kessel (1985)
Leucaena leucocephala	100-500	Dommergues (1987)
Leucaena leucocephala (in hedgerow intercropping)	75-120	Mulongoy(1986)
Leucaena leucocephala	100-130(6 months)	Sangingaetal.(1987)
Prosopis glandulosa	25-30	Rundeletal.(1982)
Prosopis glandulosa	40-50	Virginia (1986)
Prosopis lamarugo	200	Nair (1984)
Rain forest fallow	40-100	Greenland (1985)
Mature rain forest	16	Jordan etal. (1982)

and the ICRAF multipurpose tree and shrub inventory. From either of these sources, a search can be made on criteria of climatic zone, rainfall, temperature/altitude, soil limitations, phenology and uses. Lists of the better-known or economically important species are given in MacDicken and Brewbaker (1984), Brewbaker (1986), and von Carlowitz (1986a, Table 3). Non-leguminous nodulating species are given in Bond (1976).

Nutrient cycling in agroforestry systems

Figure 12 shows the soil-plant nutrient cycle adapted to the basic situation in agroforestry, that of tree and crop components. Whilst frequently represented as separate cycles for nitrogen, phosphorus, potassium and other nutrients, these are in fact strongly linked through the common elements of the plants, litter and humus. (See Frissel, 1977; Brunig and Sander, 1983; Stevenson, 1986; and for nitrogen cycling. Rosswall, 1980; Wetselaar et al., 1981; and Robertson et al., 1983.)

The cycle consists of stores, flows within the system, and gains and losses external to it. The nutrient *stores* are tree and crop shoots and roots, plant

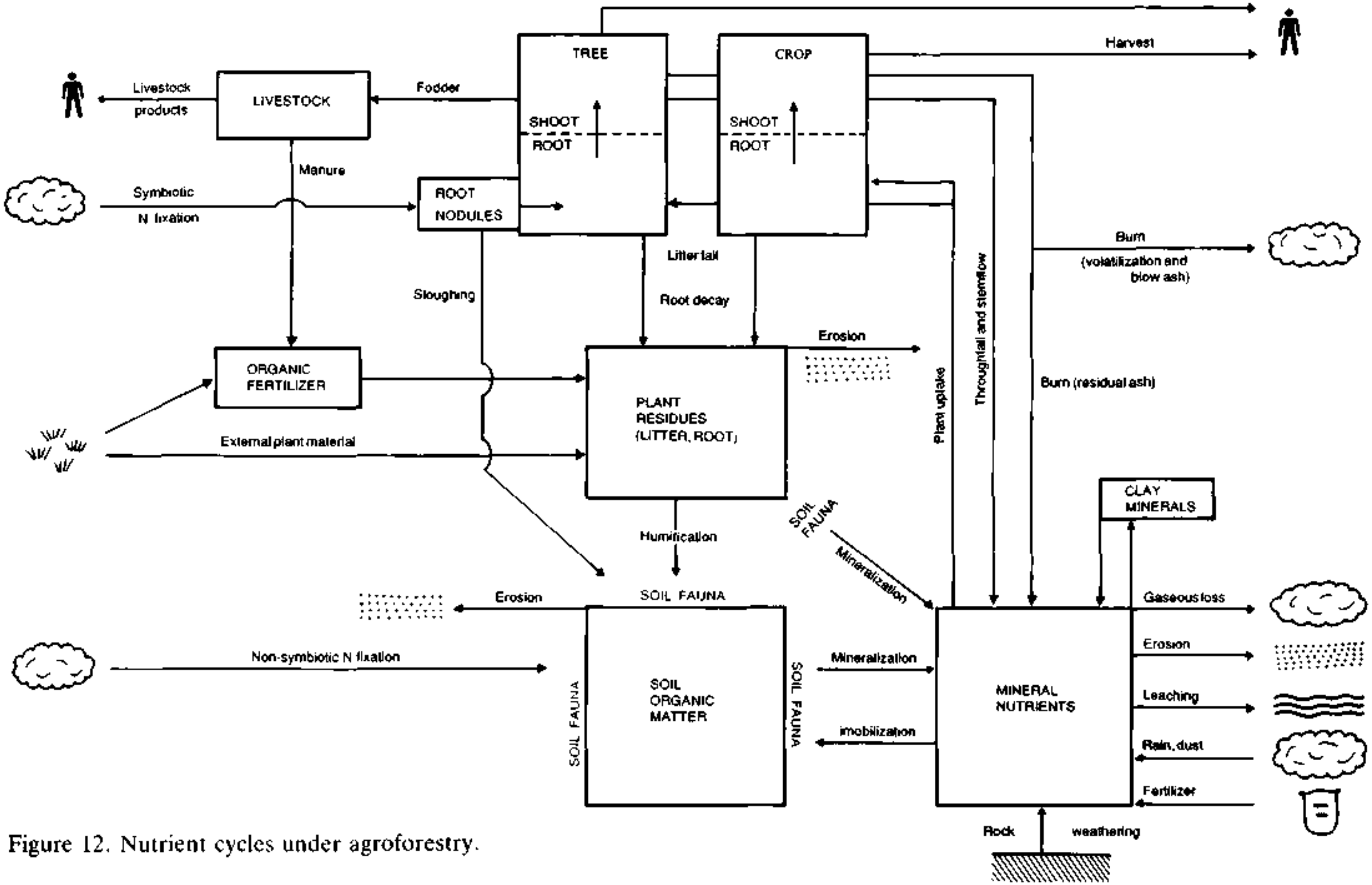


Figure 12. Nutrient cycles under agroforestry.

residues, soil fauna, labile and stable soil organic matter, secondary clay minerals (through fixation) and the store of available nutrients in mineral form in the soil solution. The main internal *flows* are from the plant components to plant residues, via soil fauna to soil humus, through the process of mineralization to mineral nutrients, and return to the plants via root uptake. Gains and losses to the soil-plant ecosystem are:

	Gains	Losses
Nitrogen:	Symbiotic fixation	Gaseous losses (denitrification) and volatilization
	Non-symbiotic fixation	Burning (also sulphur)
Other nutrients:	Rock weathering	
All nutrients:	Rain and dust	Leaching
	Organic material from outside the system	Erosion
	Fertilizer	Harvest (including fodi

The major difference in external sources of gains is between the atmosphere for nitrogen and rock minerals for other nutrients. With respect to losses, nitrogen and sulphur are largely lost if burning occurs, whilst other nutrients are retained in the system. All nutrients are liable to leaching loss from the mineral store in the soil solution, to losses in erosion, both where contained in humus and clay minerals and as dissolved minerals in runoff water. Immobilization by fixation in secondary clay minerals is of greater importance in the cycles of phosphorus and some of the micronutrients.

A key feature is that a high proportion of nutrients present in the soil at any one time is held in organic form; for nitrogen, only something of the order of 1% is in available mineral form at any one time. Once mineralized, nutrients become available for uptake by plant roots, but at the same time are highly subject to leaching.

This last feature is illustrated in a simplified diagram of the nitrogen cycle (Figure 13). Apart from that obtained directly through symbiotic fixation, nitrogen available to the plants comes from the soil mineral store, small in size and with a rapid turnover. This store is renewed from three sources: litter (above-ground plant residues and root residues), soil humus and fertilizer. The litter store is quite small at any one time, but renewed on an annual cycle, with large or small seasonal variations according to the seasonality of the climate. By far the largest nitrogen store is that bound up in organic molecules in the soil humus; this is mineralized slowly, at the same rate as the decomposition constant for soil carbon, 3-4% per year.

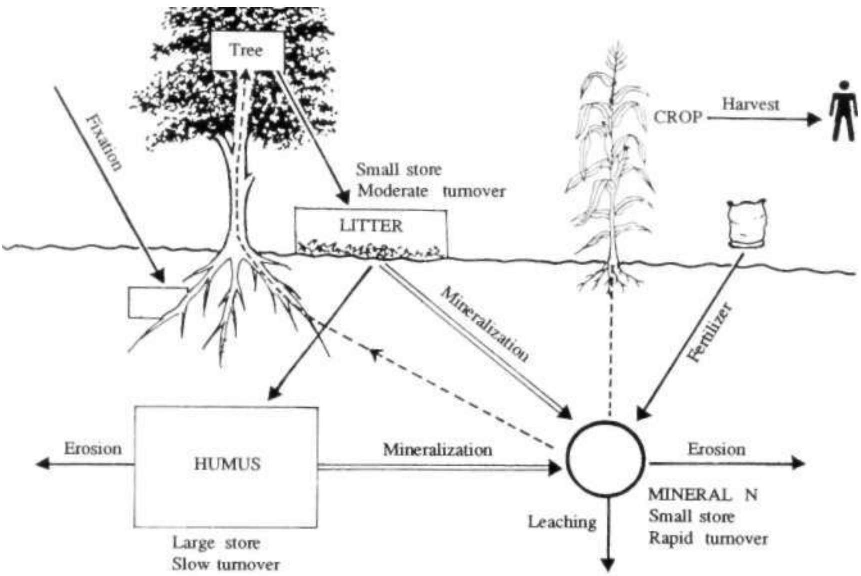


Figure 13. The nitrogen cycle under agroforestry, simplified to show major stores and flows.

The objective in designing and managing agroforestry systems is to modify cycling in such a way as to make more efficient use of the nutrients, whether these originate from natural renewal processes or from fertilizer. Specifically, it is desirable to reduce the ratio between inputs/outputs and internal cycling. Agricultural ecosystems are highly open, with inputs and outputs sometimes as much as 40% of internal cycling; natural forest ecosystems are more closed, inputs and outputs sometimes amounting to less than 10% of internal cycling. If this ratio can be reduced, nutrients are re-used more often by plants before being lost from the system.

The opportunities which agroforestry systems offer to modify nutrient cycling are:

1. To increase gains from symbiotic fixation, through the use of nitrogen-fixing trees (discussed above, a demonstrated potential of large magnitude).
2. To enhance uptake of other nutrients released by rock weathering. through the deep root systems of trees. Whilst this process no doubt exists, it is completely unknown whether its magnitude is negligible, moderate or substantial: to establish this presents a difficult challenge to experimental design.
3. To reduce nutrient fixation on clay minerals and increase availability, through release from organic compounds.

4. To lead to more closed nutrient cycling, improving the ratio between plant uptake and leaching loss, through two mechanisms:
   a. uptake by tree root systems and associated mycorrhiza, with recycling as litter;
   b. synchronizing the timing of mineralization with that of crop nutrient requirements, through controlling the quality, timing and manner of addition of plant residues.

Opportunities in two other areas appear to be considerable, although research is needed:

5. To provide a balanced nutrient supply, as organic residues, thereby reducing the likelihood of micronutrient deficiencies.
6. To reduce nutrient losses from erosion (discussed in Part II, a demonstrated potential of large magnitude).

AGROFORESTRY AND NUTRIENT CYCLING

Agroforestry systems promote more closed nutrient cycling than agricultural systems by:

- *uptake and recycling:* taking up soil nutrients by tree root systems and recycling them as litter, including root residues
- *synchronization:* helping to synchronize nutrient release with crop requirements by controlling the quality, timing and manner of addition of plant residues.

Examples

Caution is necessary in using data on leaf nutrient content. Deciduous trees translocate nutrients from leaves to perennial organs well before leaf fall, and nutrients in living leaves are usually higher than in litter (Bernhard-Reversat, 1987; Tolsma et al., 1987). Thus nutrient transfer to the soil will differ between prunings of green leaves and litter fall.

Table 23 shows some data on the nutrient content of plant parts in some trees used in agroforestry systems. If the leaf component is returned to the soil, then a typical value for tree leaf biomass production of 4000 kg DM/ha/yr gives the following values:

Nutrient	% in leaf	Potential nutrient return in leaf litter or prunings (kg/ha/yr)
Nitrogen	2.0-2.0	80-120
Phosphorus	0.2-0.3	8-12
Potassium	1.0-3.0	40-120
Calcium	0.5-1.5	20-60

Table 23. *Nutrient content (%) of multipurpose trees (Kang et al., 1984 and Buck, 1986 are secondary sources).*

Tree	Nitrogen	Phosphorus	Potassium	Calcium	Source
Acacia auriculiformis	LI .63				Buck (1986)
Acacia seyal	L2.26, LL1.63	LL0.085	L1.05, LL0.78	L1.23, LL1.93	Bernhard-Reversat (1987)
Acacia tortilis	L3.0,S6.3	L0.12, S0.38	L1.20, S0.90	L2.00, S1.00	Tolsmaet al. (1987)
Acioa barteri	L2.57	L0.16	LI.78	L0.90	Kang etal. (1984)
Acioa barteri	L2.57	L0.16	LI.78	L0.90	Wilson etal. (1986)
Albizia falcataria	L2.22				Buck (1986)
Alchornea cordifolia	L3.29	L0.23	L1.74	L0.46	Kang etal. (1984)
Alchornea cordifolia	L3.29	L0.23	LI.74	L0.46	Wilson & Kang (1986)
Brachystegia spp. etc.	L3.0, SW1.4	L0.23, SW0.43	LI.10, SW0.65		Strom-gaard (1984)
Cajanus cajan	L3.6	L0.2			Agboola (1982)
Cassia siamea	PR2.52	PRO. 27	PR1.35		Yamoah et al. (1986)
Coffea arabica	L1.6.F1.5				Aranguren etal. (1982)
Coffee+shade trees	W0.5				Borne-misza (1982)
Dalbergia latifolia	L1.78				Buck (1986)
Erythrina poeppigiana	L3.3, BR0.84	L0.18, BR0.13	LI.16, BR0.60	L1.52, BR1.15	Russo & Budowski (1986)
Erythrina sp.	LI.52, W0.9				Aranguren etal. (1982)
Fie us sp.	L1.41, W0.8				Aranguren etal. (1982)
Flemingia congesta	PR3.30	PR0.34	PR2.41		Yamoah et al. (1986)
Gliricidia sepium	L3.7	L0.2			Agboola (1982)
Gliricidia sepium	L4.21	L0.29	L3.43	L1.40	Kang et al. (1984)
Gliricidia sepium	L4.21	L0.29	L3.43	LI.40	Wilson & Kang (1986)

Table 23 (cont)

Tree	Nitrogen	Phosphorus	Potassium	Calcium	Source
Gliricidia sepium	PR4.40	PRO. 26	PR2.81		Yamoah et al. (1986)
Gmelina arborea	L2.07, WO. 22	L0.23, WO. 03	LI.16, WO. 37	L0.57, WO. 19	Chijoke (1980)
Inga sp.	LI.61, W2.28				Aranguren et al. (1982)
Leucaena leucocephala	L4.2	L0.2			Agboola (1982)
Leucaena leucocephala	L2.51				Buck (1986)
Leucaena leucocephala	L4.33	L0.28	L2.50	LI.49	Kanget al. (1984)
Leucaena leucocephala		PRO. 3	PR1.0	PR2.5, L3.0	Akbar & Gupta (1984)
Leucaena leucocephala	PR2.53				Kanget al. (1985)
Leucaena leucocephala	L4.33	L0.28	L2.50	LI. 49	Wilson and Kang (1986)
Leucaena leucocephala	L4.0				BOSTID (1984)
Leucaena leucocephala	L3.15, BR0.41	L0.15, BR0.053	LI.38, BR0.34	L1.02, BR0.39	Lulandala (in press)
Prosopis glandulosa	L2.8,W0.7				Rundel et al. (1982)
Sesbania grandiflora	L3.36-3.64				Ghaiet al. (1985)
Sesbania sesban	L2.43-4.36				Ghaiet al. (1985)
Tephrosia Candida	L3.8		L0.2		Agboola (1982)

L = leaf, PR = prunings (probably mainly leaf), W = wood, BR = branchwood, SW = stemwood, S = seeds, LL = leaf litter, natural fall, F = fruit.

Data on dry-matter yield in *Leucaena* prunings during hedgerow intercropping trials at Ibadan, multiplied by percentage nutrient content, give an annual return to the soil of about:

6000 kg DM/ha/yr x 3.00% N = 180.0 kg N/ha/yr
6000 kg DM/ha/yr x 0.28% P = 16.8 kg P/ha/yr
6000 kg DM/ha/vr x 2.50% K = 150.0 kg K/ha/yr
6000 kg DM/ha/yr x 1.49% Ca = 98.4 kg Ca/ha/yr
(Kang et al., 1985; Wilson et al. 1986).

Measurement and analyses of litter (leaf and branch) in *cacao-Cordia alliodora* and *cacao-Erythrina poeppigiana* systems in Costa Rica give annual returns to the soil of:

Cacao-Cordia:	115 kg N/ha/yr of which 71 from *Cordia*
	14 kg P/ha/yr of which 6 from *Cordia*
	65 kg K/ha/yr of which 35 from *Cordia*
Cacao-*Erythrina:*	175 kg N/ha/yr of which 122 from *Erythrina*
	9 kg P/ha/yr of which 7 from *Erythrina*
	54 kg K/ha/yr of which 27 from *Erythrina*

(Alpizar et al., 1986, 1988).

This may be compared with nutrients removed in the cacao harvest. A harvest of 626 and 712 kg/ha/yr, respectively, for the two systems comprises 19 and 26 kg/ha/yr of nitrogen, 4 and 4 kg/ha/yr of phosphorus, and 28 and 27 kg/ha/yr of potassium. These data give 'recycling-to-harvest ratios' of 6-7 for nitrogen, 1.5-1.75 for phosphorus and 1.0-1.25 for potassium. Another striking result is that for nitrogen and potassium (but not phosphorus), the amounts recycled through litter are of the same magnitude as the annual fertilizer application of 120-33-20.

Table 24 shows data on the nitrogen content of litter fall and prunings for agroforestry systems, with some natural-vegetation communities for comparison. The agroforestry data are for humid and moist subhumid climates. Under hedgerow-intercropping systems, a number of species are known which are capable of supplying 100-200 kg N/ha/yr if all prunings arc left on the soil; this is of the same magnitude as nitrogen removal in the crop harvest. Under coffee and cocoa plantations with shade trees (partly nitrogen-fixing) in Latin America, the return in litter and prunings is some 100-300 kg N/ha/yr. This is much higher than the quantities originating from nitrogen fixation. An example of stores and annual flows of nitrogen and phosphorus in a *coffee-Erythrina-Inga* system is shown in Figure 14.

In the hedgerow-intercropping study, the return to the soil in prunings is of the same magnitude as removals in harvest of intercropped cereals and legumes. For the fertilized plantation crops, the litter nitrogen exceeds removal in harvest.

Features of the nutrient cycle under natural vegetation are relevant, as representing the 'tree-only' end of a tree-crop spectrum. Figure 15 shows the phosphorus cycle as determined in a study of tropical rain forest in Panama. The amount of phosphorus that is cycling is only 6.6% of that in the soil and vegetation stores: 9.1 kg P/ha/yr is contained in litter, 11.8 if throughfall and animal remains are added, and there is a plant uptake of 11.0, compared with stores of 144 kg P/ha in the vegetation and a further 22 in the soil. The striking feature is the size of gains to and losses from the system compared with the internal cycle: 1.0 kg P/ha/yr gained in rainfall, 0.2 lost to the 'subsoil' and 0.7 in leaching, making total gains and

Table 24. *Nitrogen in litter fall and primings.*

Country and climate	Land use	Nitrogen (kg/ha/yr)	Source
Nigeria, subhumid	Hedgerow intercropping, 4 m rows, prunings:		Rang & Bahiru Duguma(1985)
	Leucaena leucocephala	200	
	Gliricidia sepium	LOO	
Nigeria, subhumid	Hedgerow intercropping, 2 m rows, prunings:		Bahiru Duguma etal.(1988)
	Leucaena leucocephala	150-280	
	Gliricidia sepium (6 months)	160-200	
	Sesbania grandiflora (6 months)	50-100	
Venezuela, subhumid	*Coffee-Erythrina-Inga* unfertilized:		Arangurenet al. (1982)
	trees only	86	
	trees+coffee	172	
	Cacao-Erythrina-Inga		Arangurenet al. (1982)
	trees only	175	
	trees+cacao	321	
Costa Rica, humid	*Cacao-Cordia alliodora* (fertilized)	115	Alpizaret al. (1986.1988)
	Cacao-Erythrina poeppigiana (fertilized)	175	
Various, humid	Rain forest	60-220	Bartholemew (1977)
Various, humid	*Leucaena leucocephala,* plantation:		BOSTID(1984)
	foliage	500-600	
	litter fall	100	
18 sites, humid	Forest	mean 134	Lundgren (1978')
Ivory Coast, humid	Rain forest	113.170	Bernhard-Reversat(1977)
Brazil, humid	Rain forest	61	Jordan et al. (1982)
USA: California, arid	*Prosopis glandulosa* (woodland)	45	Rundelet al. (1982)

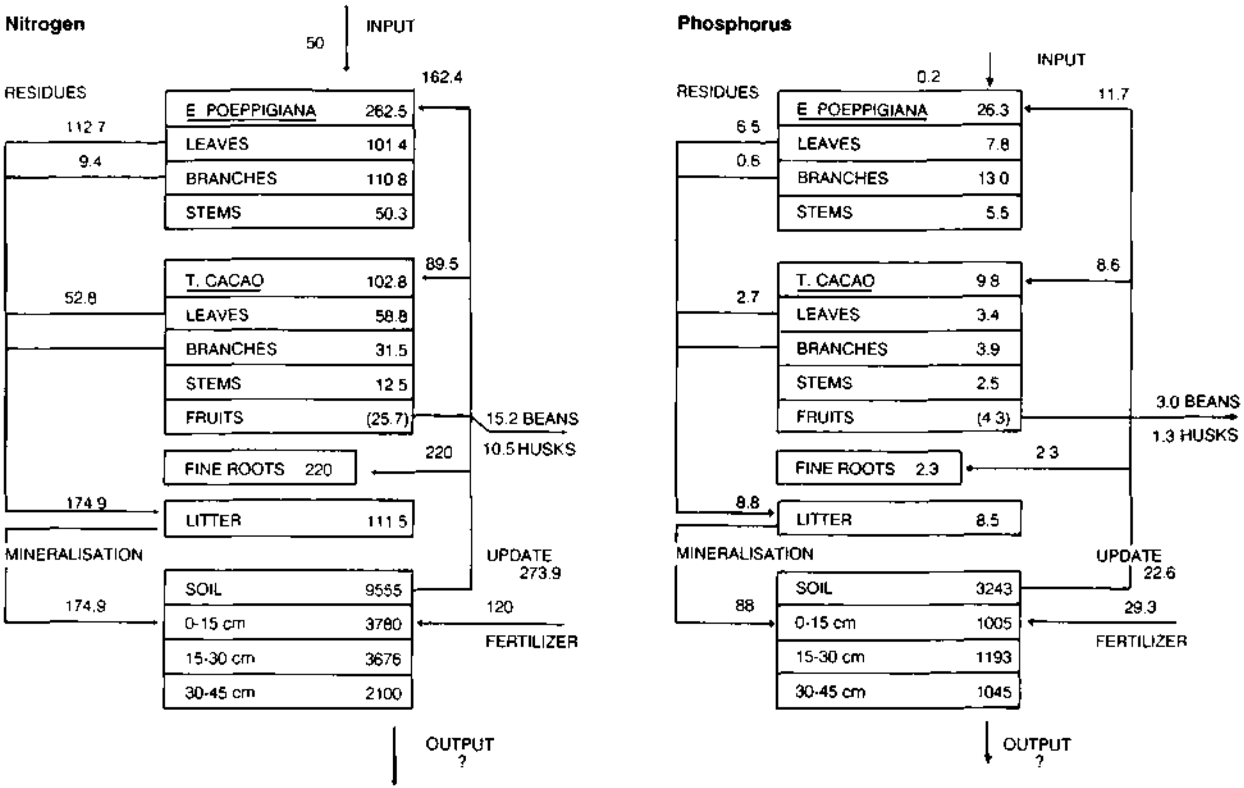


Figure 14. Nitrogen and phosphorus cycling under a *cofiee-Erythrina-Inga* system in Costa Rica (Alpizar et al.. 1986, 1988).

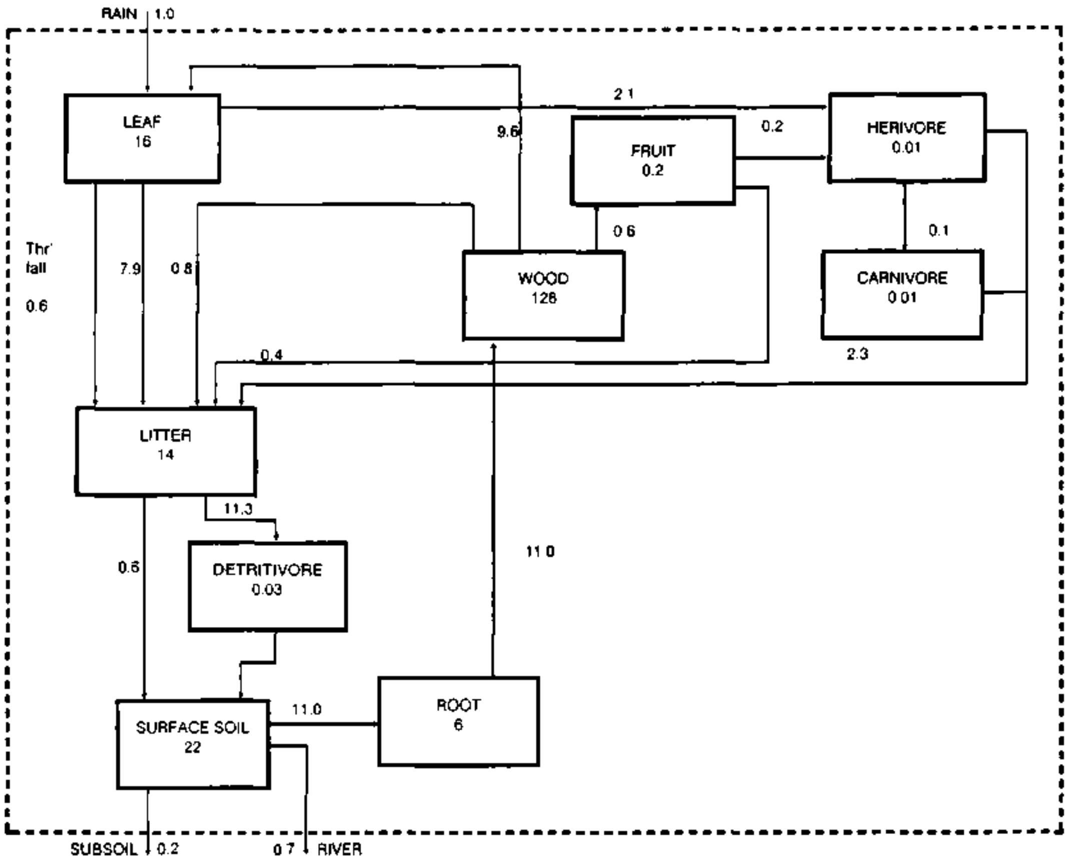


Figure 15. The phosphorus cycle under rain forest, Panama (after Golley et al., 1975).

losses only 5% of the phosphorus in the internal cycle. Corresponding figures for the potassium cycle in this study are 187.5 kg K/ha/yr cycling and gains equal to losses at 9.3, which is again 5% of the internal cycle. Thus a forest ecosystem is capable of maintaining a nutrient cycle that is 95% closed.

In very humid climates, residence times of nutrients in litter and soil are short, with rapid recycling. In rain forest, deep-rooting trees play a vital role in catching nutrients before they are leached out of the system.

In savannas of the subhumid zone, two cycles have been distinguished, through woody and herbaceous plants. In *Burkea africana* savanna of Transvaal, on sandy ferralsols, nutrients are cycled 1.2 to 2.4 times more slowly through the woody structure than the herbaceous layer. Where there is a disturbance to the ecosystem, the trees act as a stabilizing factor (Frost, 1985; Swift et al., in press). This principle should be applicable to agroforestry systems.

Comparable data for nutrient cycling under annual cropping are dominated by the large nutrient output as harvest, sometimes by a considerable nutrient loss through erosion, and either input as fertilizer or a net loss from tbe soil. Lelong et al. (1984) give data for direct comparisons of natural vegetation with fertilized maize for three environments in West Africa (humid, moist subhumid and dry subhumid); these data are dominated by large losses through erosion on the cultivated plots; leaching losses are somewhat smaller under maize than natural vegetation, presumably because of the lower infiltration. Their results are summarized as:

Natural vegetation	Internal cycling large relative to inputs and outputs Equilibrium between inputs and outputs
Annual cropping	Internal cycling small relative to inputs and outputs Outputs greatly exceed inputs, causing net loss from the soil.

In plantation crop combinations of cacao with *Cordia alliodora* and *Erythrina poeppigiana* in Costa Rica, very low rates of leaching have been measured: 5 kg/ha/yr nitrogen, 0.4 kg/ha/yr phosphorus, 1.8—1.5 kg/ha/yr potassium and 5-21 kg/ha/yr calcium. These are amazingly low for a rainfall of 2000 mm and water flow through the soil of 800-900 mm, amounting to less than 5% of the plant uptake (Imbach et al., in press).

Numerous studies have shown substantial negative nutrient balances, unless compensated by fertilizers, in systems of permanent and semi-permanent annual cropping. The nutrient balances obtained for various climatic zones of West Africa, summarized by Pieri (1983, 1985) and Roose (1979, 1980) are examples. There is a need for thorough studies of all components of nutrient cycling in agroforestry systems, with agricultural plots for comparison. The only example known for agroforestry is Alpizar et al. (1986, 1988).

Up to the present, most attention has been concentrated on the potential of nitrogen-fixing trees, with their clearly demonstrated capacity to enhance nitrogen input to the plant-soil cycle. This has led to an over-emphasis on this one aspect, and substantial research into the effects of tree/crop systems on other nutrients, particularly phosphorus, is now called for.

It is impossible to answer the many questions on nutrient cycling until data are available for a range of agroforestry systems and under different environments. The need is for quantitative determinations of balances, covering plant and soil stores, inputs, outputs and within-system transfers, along the lines of the comprehensive studies available for natural vegetation (e.g. Bernhard-Reversat, 1977, 1982; Jordan, 1982; Rundel et al., 1982), agricultural systems (e.g. Frissel, 1977; Pushparajah, 1981; Pieri, 1985; Idessaet al., 1985; Agamuthu and Broughton, 1985), and the few examples for agroforestry systems cited above, most notably Alpizar et al. (1986, 1988).

Chapter 11
Other Soil Properties and Processes

Soil physical properties

Soil physical properties form a single, interactive complex, the basis for which is the degree of aggregation between particles and the volume and size distribution of pores. Aggregation and pore space determine structure, consistence, bulk density and porosity, which in turn are linked to available water capacity, permeability, soil drainage (aeration) and resistance to erosion. A well-developed soil structure, besides aiding tillage, provides favourable conditions for development of fine feeder roots and mycorrhizae, so increasing efficiency of nutrient uptake. Key features for development of favourable physical properties are to promote, first, the existence of stable aggregation between particles, and second, a mixture of fine pores (<50 u.m) which retain moisture against gravity, and coarser pores to permit drainage of excess moisture and thus oxygen supply to roots.

The factors which determine these physical properties are soil texture, the kinds of clay minerals present and the amount of organic matter, this last supplying the natural gums which bind particles together. Texture and clay minerals are largely determined by natural soil-forming factors and processes. The opportunity to influence physical properties through management therefore lies mainly through maintenance of soil organic matter.

The effects of soil physical properties on root growth, the soil water regime, erosion resistance and crop yields are reviewed in Lai and Greenland (1979). There is ample evidence that degradation of structure and pore space can substantially reduce crop yields, even if the indirect effect on root development and nutrient uptake is excluded. Severe degradation of physical properties leads to formation of pans or crusts, reducing infiltration, decreasing erosion resistance and hindering germination of seedlings.

Such effects arise on most soil types, but are of particular importance on very sandy soils (regosols and arenosols) and heavy clays (vertisols and many gleysols). They are relatively less important on soils where the presence of free iron oxides leads to strong and stable aggregation (nitisols and some ferralsols). If organic matter is reduced, sandy soils lose what little aggregation they possess and become still more drought prone. Heavy clays naturally tend towards large and hard soil aggregates, difficult tillage and poor internal drainage, but these problems are reduced if organic matter content is maintained.

There is clear evidence for the favourable influence of trees on soil physical properties. This is, first, the invariably good physical condition of soils under natural forests, and secondly, the observed decline in physical properties following forest clearance (Lai et al., 1986). This provides a strong *a priori* indication that agroforestry systems are likely to have a favourable influence on physical properties.

Direct evidence, in the form of quantitative observations linked to control plots, is scanty. Improved water-holding capacity has been reported beneath *Acacia alhida* (Felker, 1978). Soil aggregation was measured on four-year-old plantations on an acrisol in Brazil, established on land cleared from natural forest; the degree of aggregation increased, compared with forest, under *Pinus caribaea* but decreased under both oil palm and rubber (Silva, quoted in Sanchez, 1987, p. 213).

A striking result comes from hedgerow-intercropping trials of maize with *Gliricidia, Flemingia* and *Cassia* on a ferric luvisol at Ibadan, Nigeria (Yamoah et al., 1986b). Besides hedgerows from which prunings were applied to the soil, there were control plots of two kinds: hedgerows present but prunings removed, and maize without hedgerows. On unfertilized plots with prunings removed, maize grew better close to the hedgerows than in the middle of the alleys; and furthermore, maize growth was better on plots with prunings removed than on controls without hedgerows. Maize root growth was less without hedgerows (Table 25).

Table 25. *Effect of hedgerows on root weight of intercropped maize, Ibadan, Nigeria (Yamoah et al., 1986b).*

Hedgerow species	Prunings	Maize root weight (g/plant) 3 weeks	8 weeks
Gliricidia sepium	Removed	0.29	0.83
Flemingia eongesta	Removed	0.25	1.24
Cassia siamea	Removed	0.14	0.81
Gliricidia sepium	Retained	0.36	1.24
Flemingia eongesta	Retained	0.30	1.80
Cassia siamea	Retained	0.19	0.89
Control, no hedgerows		0.11	0.58
Least significant difference (LSD) (P = 0.05)		0.11	0.51

The conclusion from this last study may be quoted, and suggested as also applicable to other agroforestry practices:

> The significance of an hedgerow-intercropping system should therefore be viewed in the light of its improvement in both the

> physical and chemical properties of the soil. The improvement in soil physical properties...may prove more important in many cases than the supply of nutrients, for the nutrients released by primings become useless if the soil physical properties do not favour proper root development to tap these nutrients. A study into the effects of alley shrubs on soil physical properties is highly recommended (Yamoah et al., 1986b).

Acidity

A strongly acid soil is one with a pH of less than 5.0. Below this value, Al^{+++} ions progressively replace H^4 ions, becoming predominant at around pH 4.0. For this reason, strong acidity is also referred to as aluminium toxicity (Sanchez, 1976, Ch. 7). Problems related to soil acidity are of two kinds: making productive use of soils that are naturally strongly acid, and checking acidification caused by fertilizers and agricultural use.

The naturally acid soils of the humid tropics, ferralsols and acrisols, are for the most part under crops which tolerate strong acidity, such as tea and rubber. The major problem is found where strongly acid soils occur in the moist subhumid zone, under conditions climatically suited to maize and other non-tolerant crops; examples are the *cerrado* soils of the Mato Grosso, Brazil, and the acid, sandy soils of Northern Province, Zambia.

A degree of acidification commonly occurs under agricultural use, but can become severe with repeated application of some kinds of fertilizer, notably ammonium sulphate. This is a hazard for the agricultural use of soils of both moderate and strong acidity.

Thus there are two distinct problems:

1. Can agroforestry systems raise the pH of already acid soils?
2. Can agroforestry systems help to check acidification?

The reason for supposing that trees may be able to check acidity lies in the concentration of calcium and of other bases in their leaves, drawn from deeper soil layers and recycled to the surface.

In fact, trees do not necessarily check acidity: soils under natural rain forest frequently have a pH of 4.0-4.5. Forest clearance on acid soils commonly leads to a reduction in acidity through the addition of bases in burnt or decomposing litter. This is normally followed by increasing acidity during cultivation as the added bases are leached. If a soil is naturally acid, this can be temporarily checked by liming, but the processes tending to restore the natural condition are powerful and persistent.

One traditional agroforestry system does successfully reduce acidity. This is the *chitemene* system of shifting cultivation found in Zambia and some adjacent countries in the subhumid zone. Trees and shrubs from natural savanna growth are felled, piled up onto part of the area from which they have come, and burnt. Rises of up to 2.0 pH points have been recorded (Stromgaard, 1984, 1985). However, this results from the release of bases which have not only come from a larger area than the cultivated land, but have accumulated in some 20 years of tree growth.

There are various approximate rules for determining the lime requirement' of an acid soil. Sanchez (1976) suggests that for every milli-equivalent (meq) of exchangeable aluminium present in the soil, 1.5 meq of calcium should be applied, or 1.65 t/ha of $CaCO_3$ equivalent. The lime requirement needed to raise topsoil pH by 1.0 points is typically 5 t/ha, and needs to be repeated approximately every five years.

This may be compared with a tree biomass production of 10 000 kg DM/ha/yr, typical for the moist savanna zone, and a mean tissue calcium content of 1% (higher for leaves, lower for other parts). This gives an accumulation of calcium, in a complete tree cover, of 100 kg Ca/ha/yr, equivalent to 250 kg $CaC0_3$ or somewhat more of lime fertilizer. This is only one twentieth of a typical lime requirement. In many agroforestry systems, notably hedgerow intercropping, the tree cover is well below 100%. Moreover, the bases contained in the litter have necessarily been extracted from the soil.

Thus, the influence of trees on soil acidity is in a favourable direction, but is unlikely to be of a sufficient order of magnitude to have an appreciable effect on soil acidity. It is therefore very doubtful if tree litter can be a significant means of raising pH on naturally acid soils.

The situation is different with respect to checking acidification. In the first place, if the tree component is employed as the means for fertility maintenance, then no tendency towards acidification should arise. Secondly, where fertilizers lead to a trend towards acidification, this is of the order of 0.1 pH points per year. The recycling of bases in tree litter could quite probably be sufficient to counteract an effect of this magnitude.

Many of the trees commonly used in agroforestry have a moderate level of calcium in their tissues. *Gmelina arborea* appears to have a particular potential. For plantations at two sites in Brazil, 117 and 161 kg Ca/ha/yr were returned to the soil in litter (Chijoke, 1980). On an acrisol at Para, Brazil, topsoil pH and calcium were measured under forest, after forest clearance, and after eight years under a *Gmelina arborea* plantation, with results (Sanchez and Russell, 1978) as follows:

	Forest	After clearance	After 8 years under *Gmelina*
pH	3.9	4.8	5.1
Ca,kg/ha	50	480	800

Vegetation clearance and burning

The opening up of new land, whether for shifting cultivation, agriculture or agroforestry, requires vegetation clearance. It is well established that manual methods of clearance (slash and burn) are better for soil properties (physical and chemical) than clearance by bulldozer; if mechanical clearance is economically necessary, cutting of trees close to the ground by a shear blade is as good as, or better than, manual cutting. If substantial parts of the vegetation are harvested, the stored nutrients are necessarily low (Seubert et al., 1977; Mueller-Harvey et al., 1985; Lal et al., 1986; Kang and Juo, 1986).

Burning causes loss in gaseous form of most carbon, nitrogen and sulphur held in the plant biomass, whereas phosphorus, potassium and calcium are retained in the ash. It was formerly assumed that nutrients in the ash were all released into the soil. However, in a hot burn there may be substantial further loss in particulate form, ash being carried up by heat and blown away by wind; substantial losses of potassium, calcium and, especially, phosphorus can occur in this way (P.K. Khanna, personal communication). An incomplete or light burn accelerates the mineralization of nutrients, as compared with litter decay, and may lead to small rises in carbon and nitrogen. On the other hand, a very hot burn can oxidize some of the soil organic matter. In the *chitemene* system of the subhumid zone, the benefits of burning are not only due to ash fertilization; burning on corrugated iron sheets and removing the ash can improve crop yields! There appears to be nutrient mobilization due to heat, and possibly enhanced retention of nitrate-N as a result of suppression of microbiological activity (Andriesse et al., 1984, 1987; Stromgaard, 1984, 1985; Andriesse, 1987; Chidumayo, 1987).

A recent suggestion is to allow the forest biomass to decompose under a leguminous cover crop. This would be of great potential benefit to the soil in avoiding the large loss of carbon and nitrogen that occurs in burning (von Uexkull, 1986). The effects of clearance on soils was the topic of a recent symposium sponsored by the International Board for Soil Research and Management (IBSRAM, 1987).

Burning of cleared vegetation permits crops to be grown in three difficult environments: acid soils, strongly leached soils of the rain forest zone and highly weathered plateau sandveld soils of the savannas. However, because of the loss of organic matter and some nutrients, and sometimes inefficient recycling of others, it is unlikely to have a place in most modern agroforestry systems.

A possible approach in agroforestry is, when clearing, to leave shelterbelts of natural vegetation. This has attractions with respect to soil conservation, but its practicability has yet to be explored.

Erosion control and soil fertility

The potential of agroforestry for the control of soil erosion has been discussed above. In the present context, the major conclusions are:

1. Except in extreme cases, the major adverse effect of erosion is lowering of crop yields through loss of organic matter and nutrients in eroded sediment and runoff. For a given rate of soil loss, effects on fertility are greater in tropical than temperate soils, and greatest on highly weathered tropical soils.
2. There is a substantial potential for reducing erosion through the use of agroforestry-based methods.

The magnitude of nutrient losses is such that to allow erosion to continue is like fertilization in reverse: it is equivalent to *removing* from the land several bags of fertilizer every year! The financial cost, in additional fertilizer or lost crop production, is apparent. Therefore, among the various means for *maintaining fertility* through agroforestry, one of the most important is through its potential to control erosion.

Chapter 12
The Role of Roots

Root biomass, turnover and nutrient content

A trend in plant science in recent years has been recognition of the importance of roots as a component in primary production. This has much significance for soil fertility, both in general and specifically for agroforestry systems.

Tree root systems consist of: (1) structural roots, of medium to large diameter and relatively permanent; (2) fine or feeder roots, 1-2 mm in diameter; (3) very fine root hairs; (4) mycorrhizae. Three features of root systems are significant: biomass, turnover and nutrient content.

The root biomass of trees is typically 20-30% of total plant biomass (equivalent to 25-43% of above-ground biomass, or a shoot:root ratio of 4:1 to 2.33:1). It can be as low as 15% in some rain forests, has been measured as 35-40% in moist savanna, and can rise well above 50% in semi-arid vegetation. Data based on core sampling can greatly under-estimate roots, as compared with complete excavation. Plants reduce their shoot growth relative to roots on sites low in nutrients, raising the root percentage (Huttel, 1975; Klinge et al., 1975; Lamotte, 1975; Jordan and Escalente, 1980; Reichle, 1981; Koopmans and Andriesse, 1982; Jordan et al., 1982; Atkinson et al., 1983; Mellilo and Gosz, 1983; Bowen, 1985; Cannell, 1985; McMurtrie, 1985; Szott et al., 1987c).

The fine-root (< 2 mm diameter) biomass of two-year-old trees grown at Morogoro, Tanzania (subhumid climate), was compared with that of a maize crop and of six-year-old *Leucaena* as follows (kg/ha) (Jonsson, 1988):

Maize	302	*Eucalptus camaldulensis*	646
Eucalyptus tereticornis	531	*Leucaena leucocephala* (Site 2)	744
Prosopis chilensis	554	*Cassia siamea*	780
L. leucocephala (Site 1)	616	6-yr-old *Leucaena*	1276

Such data, however, refer to the root biomass observed at one time. Annual net primary production of roots is substantially more than the standing biomass found at any one time. This is partly through exudation but mainly because fine roots are sloughed off, especially during periods adverse to growth. Some feeder roots begin to decay within a few days of growth. Because of this turnover, the proportion of photosynthesized carbon which passes into the root system is substantially higher than the ratio of standing biomass. For example, in Venezuelan rain forest, roots were estimated to make up 15% of standing biomass but 25% of biomass increment. In natural and plantation forests, roots may account for 30-70% of total biomass production (Coleman, 1976; Hermann, 1977; Sauerbeck and Johnen, 1977; Sauerbeck et al., 1982; Bowen, 1984, 1985; Clarkson, 1985; Fogel, 1985; Huck. 1983).

It is difficult to distinguish exudate, *sensu stricto,* of material in solution from the sloughing of cells from root walls. Estimates of the percentage of total plant dry matter production that is lost by exudation and sloughing combined range from 2 to 20% (Nye and Tinker, 1977; Curl and True love, 1986). In a coffee plantation with shade trees in Venezuela, root production in the upper 7.5 cm of soil was measured at 6600 kg/ha/yr, with much *seasonal* variation in the living root biomass, indicating turnover (Cuenca et al., 1983).

Thus there is an element in rooting systems partly resembling the shedding of leaf litter. In trees, the structural roots are comparable with the trunk and branches in having a steady increment with a low turnover, but the feeder roots are analogous with leaves, fruit and flowers, in being subject to shedding and regrowth.

The third feature of significance is that an appreciable proportion of the plant nutrient store is contained in the root system. In rain forest on a ferralsol, 10% of plant nitrogen occurred in the root system, and in forest on a podzol low in nutrients, 40% (Jordan et al., 1982). Nutrients in the root system on two sites in successional forest were as follows (Koopmans and Andricsse, 1982):

	Percentage of plant biomass nutrients in root system			
	N	P	K	Ca
Sn Lanka	16	9	13	17
Sarawak	13	28	18	12

Averaged for the two sites, the percent nutrient content and root nutrient biomass were: nitrogen 0.67%, 76 kg/ha; phosphorus 0.04%, 3.5 kg/ha; potassium 0.57%, 53 kg/ha; calcium 0.90%, 122 kg/ha (Andriesse et al., 1984, 1987).

A further possible process is the transfer of assimilate from the roots of one plant to another, possibly via mycorrhizai bridges. If it occurs, this would short-circuit exudation into the soil solution and normal root uptake by another plant (Fitter, 1985).

Mycorrhizae

Mycorrhizae are symbiotic associations between plant roots and soil fungi. The ectomyeorrhizae remain external to the host roots, the endomycorrhizae penetrate them. Among the latter, vesicular arbuscular mycorrhizae (VAM) are the most common, and have the greatest potential impact on plant nutrition.

Mycorrhizae absorb carbohydrates from the host plant. In return, they effectively expand the plant's root system, assisting in the extraction of nutrients from the soil. Nutrient ions only travel short distances in soil, hence this expansion of the root system allows a larger nutrient pool to be tapped, and can thus increase uptake relative to leaching. Mycorrhizae are of particular value in improving plant access to phosphorus, because of the very short transmission distance of phosphate ions in soil. This applies also to phosphate added as fertilizer (ILCA, 1986).

Natural plant-soil communities contain mycorrhizae adapted to the local environment. For planted trees, inoculation may be necessary; where suitable strains are absent, the effects of mycorrhizal inoculation on growth may be spectacular. Inoculation is common practice in coniferous plantation forestry, but may be necessary also in agroforestry. Thus for high rates of growth and nitrogen fixation on a ferralsol, effective *Rhizobium* inoculation and mycorrhizal colonization were found to be essential (Purcino et al., 1986). The decay of mycorrhizal hyphae is also a pathway for return of nutrients to the soil (Fogel, 1980).

Root competition for nutrients

A possible problem in agroforestry systems of all kinds is competition for nutrients between the root systems of trees and adjacent herbaceous plants. Whilst this effect is plausible, and commonly quoted, there is little evidence as to where it occurs and how severely. Most experimental work to date has failed to separate nutrient competition at the tree/crop interface from the effects of shading, moisture competition and nutrient recycling by litter.

Nutrient competition between root systems can be modelled (Gillespie, in press). Nutrients move through the soil by diffusion and mass flow. Phosphorus has the slowest rate of movement, potassium intermediate and nitrate-nitrogen the most rapid. This causes phosphorus to have high concentration gradients around roots, where nitrogen has lower gradients and thus more extensive soil depletion. Higher soil-water content increases diffusion rates and thus inter-root competition. Thick roots deplete adjacent soil nutrient pools, whereas fine roots (and mycorrhizal hyphae) produce steeper concentration gradients in the immediately surrounding soil.

Nutrient competition occurs where depletion zones extend more than half the distance between roots. It is therefore most likely to occur for nitrogen, less for potassium and least for phosphorus. The mean half-distance between roots, r, is approximately given by:

where Lv is the rooting density (cm/cm^3). Rooting densities of trees are typically an order of magnitude lower than those of cereals and herbaceous legumes, e.g. 0.5 cm/cm' for *Robinia pseudoacacia* compared with 5 cm/ cm^3) for cereals (and 50 cm/cm^3 or more for some grasses). Combining trees with crops would give additive rooting densities of 5-10 cm/cm and mean half inter-root distances of 0.25-0.18 cm. Under these conditions, inter-plant competition would be likely to occur for nitrogen, possibly also for potassium, but not for phosphorus (Gillespie, in press).

Rooting densities and distribution for a given plant will vary with soil type, moisture regime, and whether the soil is relatively fertile or degraded. If information of rooting densities of specific trees and crops is obtained, it will become possible to model nutrient competition and use this information in agroforestry design.

Roots and soil fertility under agroforestry

The functions of roots in soil fertility are to contribute to maintenance of soil organic matter and physical conditions and to take up nutrients and water. For trees, the nutrient role includes taking up nutrients from deeper soil layers, returning them, via litter, to the soil surface, and increasing the ratio of uptake to leaching loss. There is a further indirect function of stabilizing the soil, thereby reducing nutrient loss in erosion.

The return of root residues provides an input to soil organic matter even where all above-ground residues are removed. This is one reason why low-input agricultural systems do not totally cease to function. Even where crop residues are removed, part of the organic matter that has been gained through photosynthesis and translocated to the roots is transferred to the soil. The most soil-degrading land-use system the author has seen was a *Eucalyptus* plantation in Vietnam where litter was collected, and at harvest, not only were stems, branches and bark removed, but the root systems dug up for fuel.

The effects of rate of root growth and turnover on soil organic matter are illustrated by computer modelling of a temperate woodland community (beech, in Denmark). This model was run for 300 years to reach equilibrium conditions. The uncertainty over root inputs was handled by a sensitivity test. Halving the estimate of fine root input decreased the equilibrium humus value by 29%, doubling it increased the humus equilibrium by 60% (Petersen et al., 1985).

In shifting cultivation systems, the standard picture of soil organic matter is of a sharp fall during cultivation. This is matched by a steady build-up during the fallow period, giving a saw-tooth pattern. Computer modelling, using the SCUAF model (Chapter 15), produces a different picture. The rise in soil organic matter during the forest fallow is slow, since most of the plant increment is taken into the standing biomass. The main restoration comes at felling when, even though most of the above-ground material is lost in burning, the residual root mass dies back and is transformed to soil organic matter. In place of the conventional saw-tooth picture, the pattern is more nearly one of intermittent peaks, with a repeating input from root decay followed by loss under cultivation.

Data comparing roots with leaf biomass (but not total above-ground biomass) for a range of land-use systems in Costa Rica and Mexico are shown in Table 26. In five of the nine systems, roots exceed leaves, including three of the four agroforestry systems. The absolute biomass of roots in agroforestry is more than twice that of all agricultural systems reported; given the known fact of root turnover, this is important with respect to the amount of organic matter and nutrients entering the soil.

In hedgerow intercropping, root growth in maize was observed to improve close to hedgerows on plots where shrub prunings were removed, and to be better as a whole on such plots than on control plots without hedgerows (Yamoah et al., 1986b; see Table 25 above). Whether this is related to microclimatic effects or to the effects of hedgerow roots is not known.

It is commonly asserted that rooting patterns of trees and crops should preferably differ, to reduce competition for water and nutrients. For example, at Morogoro, Tanzania (subhumid climate), fine-root distribution according to soil depth of two-year-old *Leucaena, Cassia siamea, Prosopis chilensis* and two *Eucalyptus* species was found to be similar to that of maize. The authors concluding that 'the studied tree species are likely to compete with maize.for nutrients and water' (Jonsson et al., 1988). This is by no means self-evident; mutually beneficial effects of roots could compensate for competition, and research is needed.

In sylvopastoral systems, the existence of deep tap roots allows trees and shrubs to remain in leaf throughout the dry season, providing browse

Table 26. *Leaf and root biomass (k/ha) in nine land-use systems (Ewel, 1982).*

	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	1000	1070	3120	3070	2720	2040	2450	2480
Root biomass (to 25 cm)	390	1150	410	1280	2170	2350	2720	3070	4220
Ratio: roots-leaves	1.18	1.15	0.38	0.41	0.71	0.86	1.33	1.25	1.70

at a time when all herbage is grazed or unpalatable. The contrast at such times between the condition of goats (that feed on browse) and cattle (that often do not) is striking.

A remarkable adaptation to a desert environment is found in the Sonoran Desert, California (US). With groundwater present in depth, mesquite *(Prosopis glandulosa)* develops nitrogen-fixing nodules and VAM fungi at 4-5 m depth (Virginia et at, 1986).

In those agroforestry systems in which tree foliage is removed, as will be inevitable in areas with a fodder shortage, the input of organic matter and recycling of nutrients by roots offers some return to the soil. However, modelling suggests that this alone is normally insufficient to maintain soil fertility.

The key to making the best use of root systems in agroforestry lies in maximizing their positive effects whilst reducing tree-crop competition for moisture and nutrients. The basis usually quoted is to combine shallow-rooting crops with deep-rooting trees. Nutrient competition is minimized if lateral root spread is low, but this reduces the nutrient-recovery potential of tree roots. Further discussion of this aspect of resource sharing is given by Buck (1986).

Root observations are costly in time and effort, but an understanding of the functioning of systems as a whole is impossible without them. The basic approach is one of transects across the tree-crop interface, using coring, trenching, ingrowth bags or rhizotrons (permanent trenches with a glass plate along one side). Techniques are summarized in Anderson and Ingram (in press). For specialized research, carbon-14 labelling permits measurement of root turnover (Helal and Sauerbeck, 1983).

There is a clear need for further information on this topic. Basic requirements include: (1) the assembly of systematic knowledge on the rooting biomass and patterns of tree species; (2) records of root development at the tree-crop interface under a variety of environmental conditions. It is often difficult to separate root effects from microclimatic differences, but the former can be isolated by vertical sheeting and the latter reduced by frequent pruning. Experiments comparing hedgerow intercropping with equivalent mulching achieved by manual transfer from tree plantations may help to identify specific root effects on soil.

Root research is required at stations with special facilities, but should not be confined to these. In all agroforestry research, at least sample observations of root mass and distribution should be made. The simplest method is to dig a trench across the interface at the conclusion of a trial. This is a case where a few observations are better than none at all.

Chapter 13
Trees and Shrubs for Soil Improvement

What makes a good soil-improving tree?

The question of which properties of a tree or shrub make it desirable from the point of view of soil fertility has not yet been fully answered. The properties already recognized are nitrogen fixation and, with reference to reclamation forestry, a high biomass production and good potential for erosion control. It would be valuable to have guidelines on this question, as a means of identifying naturally occurring species with a potential for use in agroforestry.

The following is not a list of properties desirable in agroforestry in general, but concerns only those which are specific to soil fertility. The properties which are likely to make a woody perennial suitable for soil-fertility maintenance or improvement are:

1. a high above-ground biomass production
2. a high rate of nitrogen fixation
3. a dense network of fine roots, either with abundant feeder roots or a capacity for mycorrhizal association
4. the existence of some deep roots
5. a moderate to high, balanced, nutrient content in the foliage
6. an appreciable nutrient content in the root system
7. *either* rapid litter decay, where nutrient release is desired, *or* a moderate rate of litter decay, where soil cover for protection against erosion is desired
8. absence of toxic substances in the foliage or root exudates
9. for soil reclamation or restoration, a capacity to grow on poor soils.

It would be desirable to set standards, as to what constitutes 'high', 'dense,' etc. for major climatic zones. Tables 20, 22, 23 and 24 provide some comparative data.

The main interaction with management, leading to a reservation over whether a high nutrient content in the above-ground biomass is desirable, lies in which parts of the tree are removed as harvest. For whatever parts are returned to the soil, whether as litter, prunings, partial return from harvest (e.g. wood shavings and bark) or via manure, a high nutrient content is desirable. But for those parts which are fully and permanently

PROPERTIES OF TREES WHICH FAVOUR SOIE IMPROVEMENT

- high biomass production
- nitrogen fixation
- a well-developed rooting system
- high nutrient content in the biomass, including roots
- fast or moderate rate of litter decay
- absence of toxic substances in foliage or root exudates.

harvested, then the lower the nutrient content, the less adverse to soil fertility. This applies *inter alia* to nitrogen-fixing species, which can even have a net negative effect on soil nitrogen if the fixed nitrogen stored in the plant tissues is harvested.

This is particularly important for trees which are high in specific elements. If, for example, a tree is found to be a calcium accumulator, then this calcium has necessarily been taken from the soil. If all plant litter reaches the soil, this could be beneficial, some of it being taken up from deep soil horizons and recycled to the surface; but if all above-ground parts are harvested, then the effect is to deplete the soil calcium.

Rate of litter decay has already been discussed. If most litter falls, or pruning is done, in the dry season, and if annual plants are being intercropped, then rapid litter decay ensures nutrient release at the important time of early growth. There is a causal link in that litter with a high nitrogen content is more likely to decay rapidly. For protection against erosion, soil cover is important, and hence a slower rate of leaf decay is desirable.

Notes on trees and shrubs

Table 27 lists tree genera and species identified as beneficial for maintenance or improvement of soil fertility. The column 'Noted by' lists trees noted as favourable for soils in previous reviews, those by Nair (1984), Huxley (1985), Sanchez et al., (1985), Sanchez (1987) and von Maydell (1986). 'HI trials' marks those species known to have been included in hedgerow intercropping trials, for which it is assumed that fertility is among the potential benefits. This range is being rapidly extended. 'NFTA' indicates those species selected as priorities for soil amendment by the Nitrogen-Fixing Tree Association (Lyman and Brewbaker, 1982). Other species were added from publications, the opinions of colleagues and personal experience.

Excluding the bamboos, Table 27 lists 32 genera and 55 species. The most clearly established are one species identified primarily by farmers,

Table 27. *Trees and shrubs for soil improvement. Noted by: N = Nair (1984), H = Huxley (1985, p. 19), S = Sanchez (1987), Sanchez et al. (1985), M = von Maydell (1986). HI trials — used in hedgerow-intercropping trials. NFTA = listed as priority for soil amendment by Nitrogen Fixing Tree Association (Lyman and Brewbaker, 1982):* x x = first priority; x = second priority.

Species	Noted by	N-fixing	HI trials	NFTA
Acacia albida	NHSM	×		××
Acacia auriculiformis		×		××
Acacia mangium		×		×
Acacia mearnsii	N	×		××
Acacia senegal	NM	×		×
Acacia tortilis	NM	×		×
Acioa barteri	N		×	
Acrocarpus fraxinifolius	H	×		
Alchornea cordifolia			×	
Albizia lebbeck	NHM	×	×	×
Albizia falcataria				×
Alnus spp., including *nepalensis, acuminata*		×		×
Anacardium occidentale	M			
Azadirachta indica	NM			
Bamboo genera				
Cajanus cajan	N	×	×	
Calliandra calothyrsus	NH	×	×	×
Cassia siamea	NM		×	
Casuarina spp., mainly *equisetifolia*	M	×		×
Cordia alliodora	NS			
Erythrina spp., including	NHS	×	×	×
poeppigiana	NS	×		×
fusca		×		××
Flemingia congesta		×	×	
Gliricidia sepium	NH	×	×	×
Gmelina arborea	NS		×	
Grevillea robusta	NH			
Inga spp., including *edulis, jinicuil, dulce, vera*	NHS	×	×	×

Tabic 27 (cont)

Species	Noted by	N-fixing	HI trials	NFTA
Lespedeza spp., including *bicolor*, *thunbergii*	N	×		
Leucaena leucocephala	NHSM	×	×	××
Leucaena diversifolia		×		×
Melia spp., including *azedarach*, *volkens*				
Parkia spp., including *africana*, *biglobosa*, *clappertonia*, *roxburghii*	NM	×		×
Parkinsonia aculeata	M			×
Paulownia spp.				
Pithecellobium dulce	N	×		×
Prosopis spp., including	NHS	×		×
cineraria,			×	×
glandulosa,		×		×
juliflora	*M*	×		×
Robinia pseudoacacia		×		
Samanea saman			×	×
Sesbania spp., including	H			
bispinosa,	N	×		
grandiflora,	N	×		×
rostrata,		×	×	
sesban		×		
Terminalia spp.	H			
Ziziphus spp., including *mauritiana*, *nummularia*	NM			

Acacia albida, and one initially selected and improved by scientists, *Leucaenu leucocephala*. On weight of evidence and opinion, species with particularly high potential are:

Acacia albida	*Gliricidia sepium*
Acacia tortilis	*lnga jinicuil*
Calliandra calothyrsus	*Leucaenu leucocephala*
Cusuarinu equisetifoliu	*Prosopis cineruriu*
Erythrinu poeppigiunu	*Sesbania sesban.*

Besides the 55 species listed, there are certainly many others which are of high value for soil improvement.

The following notes refer to soil-fertility aspects only, and are not intended as a guide to species selection. Information on environmental adaptation, phenology and range of uses is given in the ICRAF multipurpose tree and shrub inventory (von Cariowitz, 1986a, Tables 3 and 4) and reports of the Nitrogen-Fixing Tree Association (Lyman and Brewbaker, 1982; MacDicken and Brewbaker, 1984); and with special reference to the semi-arid zone by Baumer (1983) and von Maydell (1988).

Acacia

Acacia albida (synonym: *Faidherbiu albida)* is one of the two best-known soil-improving trees. It is valued by farmers in the semi-arid zone of West Africa and in the subhumid zone, for example in Senegal, Malawi and Ethiopia. Increases of 50-100% in soil organic matter and nitrogen beneath trees, as compared with surrounding soils, have been reported, associated with higher water-holding capacity. Unfertilized millet and groundnut yields can be up to 100% higher under trees. The difference is smaller if fertilized, and believed to be due mainly to nitrogen fixation. Maize and sorghum yields in Ethiopia were over 50% higher under trees, the differences being significant at under 5% probability levels. Besides preserving natural trees, *A. alhidu* has been planted in development projects (Radwanski and Wickens, 1967; Dancctte and Poulain, 1969; Felker, 1978; Kirmse and Norton, 1984; Poschen, 1986; Miehe, 1986; CTFT, 1988, ch. 12).

A. senegul (gum arabic) is employed in a system of rotational intercropping in Sudan; after four year's intercropping with food crops, the trees are left as a soil-restoring fallow for some 16 years before being felled and replanted (M.M. Ballal, personal communication).

Acacias benefit the growth of pastures and soils beneath them, notably *A. tortilis* (included in the 'top ten' above as a representative of sylvopastoral trees). To what extent its pasture and soil improvement potential is a direct effect of the tree, or is due to animals and birds resting there, is not known.

Many other acacias benefit the soil, it is believed mainly through nitrogen fixation. *A. auriculiformis* and *A. meurnsii* were identified as first priority for soil amendment by the Nitrogen-Fixing Tree Association (Lyman and

Brewbaker, 1982). *A. mangium* has a slower litter breakdown, and thus nutrient release, than most acacias.

Alnus

This is one of the few non-leguminous genera to include nitrogen-fixing species. It is partly subtropical to temperate, and valued in tropical highlands, for example Nepal and Costa Rica. *Alnus* spp. are used in restoration of derelict land.

Azadirachta

Azadirachta indica (neem) is a tree with a very wide range of uses, among which is a capacity for soil improvement. Although not a nitrogen-fixer, improvements in soil nitrogen have been observed beneath neem trees, as well as higher soil carbon and bases, and a lower pH (Radwanski, 1969; Radwanski and Wickens, 1981).

Bamboo

The definition of agroforestry includes bamboos among the 'woody perennials'. They are a common component of home gardens, where the abundant litter is likely to contribute to soil fertility. Under *Dendrocalamus* bamboo in north Vietnam, soil physical conditions are exceptionally good (personal observation). The same genus has been reported as an accumulator of potassium (Toky and Ramakrishnan, 1982). In shifting cultivation systems in north-east India, bamboos play an important role in nutrient accumulation (Ramakrishnan, in press). Given their suitability for both barrier and cover functions in erosion control, research into the possible capacity of bamboos to improve fertility is important.

Cajanus

Cajanus cajan (pigeon pea) is sometimes treated as the tree component in agroforestry, and has been used in hedgerow intercropping trials. Planted along the contour, it can be used in erosion control. At Ibadan, a pigeon pea-maize rotation not surprisingly improved soil physical properties, organic carbon and bases, as compared with continuous maize (Hulugalle and Lal, 1986).

Calliandra

Calliandra calothyrsus is a multipurpose tree valued especially in Java but grown widely. It can be established on degraded soils, leading to their improvement, and has been used in improved fallow. Reasons given are nitrogen fixation, abundant litter with rapid decay, and deep rooting with nutrient uptake (National Research Council, 1983).

Cassia

Cassia siamea has the capacity to grow on poor soils and is commonly used in hedgerow intercropping trials, although the extent of its soil-improving potential is not known. There is even doubt as to whether it is nitrogen fixing, although established opinion is that it is not. Litter is plentiful, and there appear to be no strong ill effects on adjacent crops. Given its ease of establishment, good survival, tolerance of drought and poor soils, potential in erosion control and range of uses, research into its effects on soils is desirable.

Casuarina

Casuarina equisetifolia is widely and successfully used in sand-dune stabilization and as windbreaks, and *C. glauca* in erosion control. Besides nitrogen fixation, the valuable feature is the dense root mat, which stabilizes the soil surface and, by its decay, helps to build up soil organic matter. There is a range of species adapted to different climates (National Research Council, 1984).

Cordia

Cordia alliodora is widely used in Central America, singly or in combination with *Erythrina* and *Inga*, as a 'shade tree' in coffee and cacao plantations. This appellation underestimates its functions. Even without an associated nitrogen-fixing tree, it achieves considerable recycling of nutrients through litter (Alpizar et al., 1986, 1988).

Erythrina

Erythrina poeppigiana is the main nitrogen-fixing species used in combination with coffee and cacao in Latin America. It is pruned and the prunings are used as mulch, with fertilization effects well known to farmers. Besides nitrogen fixation, there is considerable recycling of nutrients. This can include nutrients added in fertilizer, leading to its more efficient utilization (p. 176).

Eucalyptus

'*Eucalyptus*, a tree which is widely planted by farmers but not in favour with agroforestry scientists'—this adaptation of Dr. Johnson's definition of oats carries the justification for including it in notes concerned with trees and soil fertility, for the reputation of the commonly planted eucalypts (e.g. *E. camaldulcnsis, E. globulus, E. grandis, E. saligna, E. tereticornis)* is of being a cause of soil erosion or degradation. Their effects on the water cycle have also aroused strong feelings, becoming a political issue in some quarters. Farmers, however, will continue to plant eucalypts, as a fast-growing source of satisfactory fuelwood with easy establishment, good survival, and a potential for repeated coppicing.

Evidence of the effects on soils of *Eucalyptus* monocultures is summarized in a review by Poore and Fries (1985). The following are the conclusions from this review, to which reference should be made for evidence and discussion.

> Eucalypts are not good trees for erosion control. Under dry conditions, ground vegetation is suppressed by root competition. This effect is accentuated by collecting or burning of litter.
>
> Natural eucalypt forest appears to control the leaching and run-off of nutrients as well as, even perhaps slightly better than, other natural forests.... Where eucalypts are planted on bare sites, there is an accumulation and incorporation of organic matter. There is no evidence of podzolization or irreversible deterioration of soil.... [However,] the cropping of eucalypts on short rotation, especially if the whole biomass is taken, leads to rapid depletion of the reserve of nutrients in the soil. This is a direct consequence of rapid growth; it would apply in much the same way to any other highly productive crop.... The effects of eucalyptus on ground vegetation depend very much upon climate... Ground vegetation is less affected in wet conditions than in dry, when it may be greatly reduced.... There is evidence that some eucalypt species produce toxins that inhibit the growth of some annual herbs.

The above review is not concerned with effects on agricultural crops, on which there is as yet little systematic evidence. The slow breakdown of leaf litter does not in itself reduce nutrient return, and many of the adverse effects on interplanted crops may be due to shading or toxins, rather than soil fertility as such. Based on data in George (1982) and Turner and Lambert (1983), the order of magnitude for nutrient removal in whole-tree harvest of eucalypts 10 years old with a biomass of 90 000 kg DM/ha is (kg/ha) 100-400 nitrogen, 10-100 phosphorus, 100-250 potassium and 250-1000 calcium. Litter fall is low in early years, increasing at maturity. Some two-thirds of the gross annual nutrient uptake is returned to the soil in litter.

Thus, many of the adverse effects on associated crops are not due primarily to degradation of soil fertility. However, there is no reason to doubt the common view that eucalypts should not be planted in intimate mixtures with crops. Experiments are in progress in Malawi and India in which *E. lereticornis*, in a square arrangement at various spacings, is interplanted with a range of crops, the results from which will be valuable in showing the extent of crop yield reduction and, if terminal soil sampling is carried out, of soil changes.

Gliricidia

Gliricidia sepium is among the few species so far identified that may have a potential equal to *Leucaena* as a pruned shrub in hedgerow intercropping (NFTA, 1988). If laterally pruned it is less competitive, at least above ground. Favourable effects on soil properties have been observed at Ibadan, Nigeria (Yamoahet al., 1986c). In another trial at Ibadan, in which differing proportions of *Gliricidia* prunings were removed, maize yield showed a clear relation with the amount retained as mulch. In reclamation of a degraded soil, maize yields on plots with *Gliricidia* exceeded those on control plots by the third year (Atta-Krah and Sumberg, 1988). At Maha Illuppallama, Sri Lanka (moist subhumid climate) *Gliricidia sepium* used for hedgerow intercropping with maize showed considerably higher crop yields than on controls without trees (L. Weerakoon, personal communication).

Gmelina

Gmelina arborea is a valued source of poles and timber but has a depressive effect on yields of adjacent crops, possibly owing to dense shade. A field study of its effects on soils has been carried out, unfortunately with the conclusions presented in such a way as to make it difficult to assess their significance (Chijoke, 1980). As compared with previous natural forest, soil reaction slightly increased during the first six years under *Gmelina.* Large amounts of nitrogen, calcium and, especially, potassium are taken up into the growing tree, but there is also considerable return of these elements in litter. Increases in soil pH and calcium under a *Gmelina* plantation have occurred in Para, Brazil (p. 148) and current research is in progress at Yurimaguas, Peru (Perez et al., 1987). Where amelioration of soil acidity is desired, and labour abundant, it could be worth investigating the potential of growing *Gmelina* in compact blocks and manually transferring leaf litter to land under crops.

Grevillea

Grevillea robusta is widely grown as a shade tree, and planted on soil-conservation structures. Its litter decay is moderately slow. There is no evidence on effects on soil fertility, but at the least these do not appear to be adverse (Neumann, 1983).

Inga

Several species of *Inga,* notably /. *jinicuil,* are valued for nitrogen fixation and nutrient recycling in litter. These are used in combinations with coffee and cacao (p. 176). They is also being used in hedgerow intercropping.

Leucaena

The most widely used tree in modern, scientific agroforestry, particularly but by no means exclusively for hedgerow intercropping, *Leucaena leucocephala* is valued especially for its effects on soil fertility. It was used for shade and soil improvement in tree and coffee plantations in Java as early as 1900 (Dijkman, 1950). Formerly considered a tree mainly for the humid tropics, it has recently been found to equal or excel the performance of most other species in moist and dry subhumid climates and even into the margin of the semi-arid zone. It is being promoted in some areas as a substitute for fertilizer, but also, when used in combination with moderate levels of fertilizer, it improves the crop response (cereals, legumes, rice). Attack by the psyllid, *Heteropsylla cubana,* is currently serious in some regions. There can be a residual effect on the succeeding crop (Pound and Cairo, 1983; Chagas et al., 1983; Nair, 1984, p. 50; BOSTID, 1984; Kang et al., 1985; Read et al., 1985; Weerakoon and Gunasekera, 1985; Brewbaker, 1987).

Given this record of success, it is useful to note what properties relevant to soil fertility are possessed by *Leucaena:*

- high biomass production: 10 000-25 000 kg DM/ha/yr
- high nitrogen fixation: 100-500 kg N/ha/yr
- high level of nitrogen in leaves (2.5-4.0%), and thus high rate of return in litter or prunings
- substantial content of other nutrients in leaves (see Table 23)
- high biomass in the root system, possibly leading to substantial annual turnover of organic matter and nutrients (no evidence) and a favourable effect on soil physical properties.

The main soil limitation is a reduction in growth on acid soils, appreciable below pH 5.5 and serious below 5.0. Other species are more acid tolerant, including *L. diversifolia* and *L. shannoni* (Board of Science and Technology for International Development (BOSTID), 1984; Fox et al., 1985; Brewbaker, 1987). Much information is contained in *Leucaena Research Reports.*

As with all species, the magnitude of effects on soil fertility depend strongly on whether prunings are returned to the soil. Data from Ibadan, under a bimodal moist subhumid climate, show a capacity of 4-m *Leucaena* hedgerows planted 4 m apart to sustain both soil fertility and yields of intercrops, provided prunings are returned, but a decline in soil properties and crop yields if removed (Kang et al., 1985).

Parkia

In West Africa, higher crop yields are reported beneath the canopy of several *Parkia* species. These include *P. clappertonia* in Ghana (E.O. Asare, personal communication) and species in Nigeria (personal observation).

Paulownia

Paulownia elongata has been described as 'China's wonder tree'. It is grown in temperate subhumid climates (latitude 30 to 40°N). With trees spaced at 5 x 10 m, yields of intercropped wheat are as high as on land without trees, and at 5 x 20-40 m spacing, 7-10% higher. The root system is deep, mainly below 40 cm (Chin Saik Yoon and Toomey, 1986; Zhao Hua Zhu, in press).

Prosopis

Prosopis cineraria is a tree of the semi-arid to dry subhumid zones, valued in India for a variety of uses, amongst which is its effect on soil fertility. It can lay claim to being the subject of the earliest publications on agroforestry, for 'Indian scriptures are replete with a variety of references on khejri'. Its reputed effects on fertility extend beyond soils to livestock and humans!

Growth of both pastures and crops are reported as equal or better under *Prosopis* than on adjacent land. It outperforms other species in the same area in this respect. Soil nutrient content is higher beneath the trees than on adjacent open land (Table 13). There is also an improvement in organic matter, soil physical conditions and water-holding capacity (Aggarwal, 1980; Mann and Saxena, 1980).

Prosopis juliflora does not appear to equal *P. cineraria* in soil improvement, but has a high litter production and has been successfully used for reclamation of eroded land. It may, however, be competitive with adjacent crops.

Some *Prosopis* species have a remarkable capacity for biomass production and nitrogen fixation under extreme heat and drought stress. In the Sonoran Desert of California (US), a soil content of 10 200 kg N/ha under the tree canopy, compared with 1600 outside, has been recorded (Rundel et al., 1982; Felker et al., 1983).

Robinia

Robinia pseudoacacia (black locust) is a nitrogen-fixing tree that is excellent for reclamation of eroded land and soil stabilization on steep slopes.

Sesbania

At least four *Sesbania* species are employed in agroforestry, both traditional and modern. In western Kenya, 5. *sesban* is planted among crops, and there are qualitative observations of equal or greater yields beneath. 5. *rostrata,* besides root nodulation, is unique for its profuse stem nodulation, with 4000 to 5000 nodules on a 3-m stem (International Institute of Tropical Agriculture (IITA), 1983), making it a promising species for hedgerow intercropping.

Both *S. rostrata* and *S. bispinosa* are tolerant of waterlogging, and so can be employed in association with swamp rice cultivation, either planted along bunds or as a short fallow crop (Tran Van Nao, 1983; Bhardwaj and Dev, 1985).

Zizyphus

Like *Prosopis,* this shrub of the semi-arid zone is mentioned in Indian scriptures. It is valued particularly as fodder. A monograph by Mann and Saxena (1981) on *Z. nummularia* does not specifically mention soil fertility. However, foliage analyses show a quite high and balanced nutrient content which, coupled with its deep rooting habit, could make it a potentially useful species from a soil-fertility viewpoint if not harvested for fodder.

Chapter 14
Agroforestry Practices for Soil Fertility

The analytical approach to soil fertility under agroforestry adopted in Chapters 8 to 13 is only a means to an end. What matters are the effects of agroforestry systems as a whole upon soil properties, and thereby the sustainability of those systems.

It should be said at the outset that there are very few studies yet available which cover nutrient cycling and/or soil monitoring under agroforestry systems linked with control plots'under agriculture. The main groups of work to date are the experimental studies of hedgerow intercropping conducted at IITA in Ibadan, Nigeria, and the nutrient-cycling studies carried out on plantation crop combinations in Costa Rica and other Central American countries. Apart from these, results are sparse. The few trials for which data are available are mostly at an early stage and, because of soil microvariability results, are usually not statistically significant.

This situation could change markedly in five to seven years' time. A large number of agroforestry system trials have recently been started or are planned to commence, in which it is to be hoped that nutrient cycling and soil monitoring will be carried out.

Hence the following notes necessarily contain many statements which are qualitative, or plausible hypotheses. Some are sufficiently well established for the practices concerned to be adopted by farmers, but rather few have been demonstrated by accepted standards of scientific proof.

Soil-fertility aspects of indigenous agroforestry systems

A starting point is to consider the role of soil fertility in indigenous agroforestry systems. The ICRAF Agroforestry Systems Inventory contains records of some 200 systems, of which 26 have so far appeared as published full descriptions (Nair, 1984-88, 1987b, 1989).

The descriptions are listed in Table 28, with the practices that occur classified according to Table 4. They are not the result of a sampling procedure, but the balance of practices is nevertheless of interest.

Of the 42 examples of practices, 30 have a spatial-mixed arrangement of the tree component, or over 70% of the total, compared with 6 examples, or 15%, that have a spatial-zoned arrangement. The most widely

Table 28. *Soil aspects of indigenous agroforestry systems. Based on the ICRAF Agroforestry Systems Inventory (Nair, 1989). For soil aspects, small letters indicate brief mention only. For references, see Agroforestry System Descriptions (AFSD) 1-26 in the ICRAF Publications List.*

AFSD number	Country	Agroforestry practices	Compon- ents	Arrangement	Soil aspects
1,3	Tanzania	Home gardens	AS	SM	F
2	Thailand	Taungya	AS	R	a
4	Nepal	Trees for soil conservation on terraces;	AS	SZ	E
		boundary planting	AS	SZ	F,R
5	Paraguay	Trees on cropland	AS	SM	
6	Papua New Guinea	Plantation crop combinations	AS	SM	
7	Sri Lanka	Plantation crop combinations	AS	SM	e
8	Brazil	Plantation crops with pastures	SP	SM	
9	Papua New Guinea	Improved fallow;	AS	R	f
		plantation crop combinations	AS	SM	
10	Venezuela	Plantation crop combinations;	AS	SM	
		trees on pastures	SP	SM	
11	Brazil	Trees on cropland;	AS	SM	e,f
		trees on pastures	AS	SM	
12	South Pacific Islands	Plantation crop combinations;	AS	SM	
		improved fallow;	AS	R	
		plantation crops with pastures;	SP	SM	
		home gardens	AS	SM	
13	Brazil	Plantation crop combinations	AS	SM	
14	Malaysia	Plantation crops with pastures	SP	SM	f

Table 28 (cont)

AFSD number	Country	Agroforestry practices	Components	Arrangement	Soil aspects
15	India (Tamil Nadu)	Trees on, cropland;	AS	SM	F,R
		boundary planting;	AS	SZ	
		windbreaks	AS	SZ	
16	Sudan	Trees on cropland;	AS	SM	f
		trees on pastures	SP	SM	
17	Ethiopia	Trees on cropland	AS	SM	F
18	India (Kerala)	Home gardens	ASP	SM	f
19	Rwanda	Trees on cropland;	AS	SM	E,F
		boundary planting;	AS	SZ	
		home gardens;	AS	SM	
		multipurpose woodlots; (plus improved fallow, hedgerow intercropping on trial basis)	T		
20	Kenya	Taungya	AS	R	
21	Indonesia (Sumatra)	Multistorey tree gardens	AS	SM	E,F
22	India (north-west)	Trees on cropland;	AS	SM	E,F,R
		trees on pastures;	SP	SM	
		windbreaks;	AS	SZ	
		reclamation	T		
23	Sri Lanka	Home gardens	AS	SM	e
24	Nigeria	Home gardens	ASP	SM	F
25	Bangladesh	Home gardens	AS	SM	
26	Spain	Trees and pastures	ASP	SM	F

Note: Components: AS = agrosylvicultural SP = sylvopastoral, ASP = agro-sylvopastoral, T = trees predominant; Arrangements: R = rotational SM = spatial mixed, SZ = spatial zoned; Soil aspects: E,e = erosion control, F,f == fertility, R,r = reclamation or use of poor soils, A,a = adverse effects.

represented practices are tree gardens (9), trees on cropland (7) and plantation crop combinations (6), followed by two sylvopastoral practices, trees on pastures (5) and plantation crops with pastures (3). The leading spatial-zoned system is boundary planting (3). It seems that farmers, unlike scientists, prefer their trees to be randomly spaced!

The last column shows the degree of emphasis on soils aspects, as E, e = erosion control, F, f = soil fertility, and R, r = reclamation or use of poor soils. Lower-case letters denote a brief mention, capitals indicate that the aspect is described as a feature of importance.

Seventeen descriptions refer to favourable effects upon soils, of which 10 describe this as an important feature; for fertility alone, the corresponding figures are 16 and 9. Only one description refers to adverse effects on soils, a statement that tree-crop competition for soil resources contributed to crop-yield decline under taungya in Thailand.

It can be concluded that, for all the lack of 'scientific proof, maintenance of soil fertility is an identified feature of a substantial proportion of indigenous agroforestry systems.

INDIGENOUS AGROFORESTRY SYSTEMS

The majority of indigenous agroforestry systems are either rotational, as in shifting cultivation, or of the spatial-mixed type. This contrasts with the spatial-zoned arrangements frequently favoured in on-station experimental work. There is food for thought in this situation.

Maintenance of soil fertility is a feature of most indigenous agroforestry systems and is recognized to be so by the farmers.

Soil-productivity aspects of eight practices have previously been reviewed by Nair (1984): shifting cultivation, planted tree fallow, taungya, trees on cropland, plantation crop combinations, hedgerow intercropping, trees for soil conservation and windbreaks, with shorter notes on some other practices. A review of South American agroforestry systems, with discussion of soil fertility, is given by Hecht (1982).

Soil fertility under specific agroforestry practices

Rotational practices

Shifting cultivation. This is the earliest and still the most widespread practice of agroforestry. There have been many case studies and reviews of the restoration of soil fertility by natural fallows, classics among which are studies based on forest in Zaire (Bartholemew et al., 1953) and the forest and savanna zones of West Africa (Greenland and Nye, 1959; Nye and

Greenland, 1960). An FAO (1974) symposium is also of particular value. For data on soil changes, some notable recent studies are:

North-east India	Ramakrishnan and Toky (1981) Mishra and Ramakrishnan (1983) Toky and Ramakrishnan (1983)
Nitrogen cycling, 4 sites	Gliessman et al. (1982)
Three Asian sites	Andriesse (1987)
	Andriesse et al. (1984,1987)
Thailand	Kyuma et al. (1985)
Zambia, *Chitemene* in the savanna zone	Stromgaard (1984,1985)
Peru	Szottetal. (1987c)

The basic findings are well known. Shifting cultivation is a sustainable system, provided that the fallow is long enough to restore soil conditions to the same state as in previous cultivation-fallow cycles. The relative lengths of cultivation and fallow are expressed as the R factor, and for any given combination of climate and soil there is a critical level for the ratio of cultivation to fallow, the soil rest-period requirement (Table 12, p. 87). If the actual R value rises above the rest-period requirement, soil degradation occurs, becoming progressively worse in successive cycles. Estimates of the rest-period requirement under low-input systems of agriculture are high, such as to make the continuation of shifting cultivation by traditional methods unrealistic under modern ratios of population to land. Savanna vegetation is less efficient at restoring fertility than forest.

The cycle of soil changes was formerly thought of as a progressive build-up of soil organic matter and nutrients during the fallow, corresponding to the increase in forest biomass. This is correct for carbon and nitrogen, but for other nutrients much of the increase goes into the vegetation and is only released to the soil upon clearance and burning. One study found that nitrogen did not decrease during cultivation, a result attributed to release through decomposition of residual tree trunks (Jordan et al., 1983).

In Thailand, soil carbon, nitrogen and phosphorus were found to reach their lowest levels three to four years after the beginning of fallows (Nakano and Syahbuddin, in press). When the same methods were applied to three south-east Asian sites with annual rainfall of 900-1200, 1560 and 4000 mm, considerable differences in nutrient-recycling mechanisms were found (Andriesse et al., 1984, 1987; Andriesse, 1987). We are far from knowing all the answers about traditional shifting cultivation.

The effects on soil properties of methods of vegetation clearance and burning have been noted (p. 148). The key features are that burning is effective in producing a rapid release of nutrients when required; but is inefficient in terms of the loss of nitrogen and plant carbon.

An early attempt at improving shifting cultivation was the corridor system, in which the fallow is still natural forest regeneration, but the area cleared for cultivation is a belt along the contour, moving up the slope in successive years to produce contour-aligned belts of forest at different stages of regeneration (Jurion and Henry, 1969). Whilst achieving erosion control, this does not in itself change the rest period requirement and thus the sustainable population:land ratio. More radical attempts to improve shifting cultivation take it into the class of improved tree fallow.

Improved tree fallow. Reasons for using a rotation of crops with planted trees, in place of colonization by natural vegetation, may be to obtain harvested products from the trees, improve the rate of soil amelioration, or both. To the extent that parts of the tree are harvested, as forage or fuelwood, the capacity for soil improvement will be reduced. The length of planned fallows was first discussed by Ahn (1979).

Long rotations of this kind are uncommon. Most examples are not simple alternatives of trees with crops, but involve an element of spatial intercropping. In an agrosylvopastoral system from Ecuador, two years of food crops are followed by eight years of a fallow consisting of *Inga edulis* interplanted with banana and a forage legume, the last being grazed by pigs. The litter from *Inga* is assumed to improve soil fertility (Bishop, 1982). Early-stage data from Peru show that biomass production from *Inga* overtakes that of herbaceous fallows and equals or exceeds natural forest (Szottetal., 1987b).

In the *Acacia Senegal* system of Sudan, trees are interplanted with food crops, and crop production continues for four years. This is followed by some 16 years during which the trees are tapped for gum arabic and soil fertility builds up (M.M. Ballal, personal communication).

Short, sub-annual tree fallows are also possible. Tree fallows amid rice were a traditional practice in north Vietnam (Tran Van Nao, 1983). In north-west India, *Sesbania cannabina,* grown under irrigation for 65 days between wheat and rice crops, added 7300 kg DM/ha and 165 kg N/ha (Bhardwaj and Dev, 1985).

A question of fundamental importance for agroforestry design is the relative efficiency in soil improvement of a rotational tree fallow and a spatial, concurrent arrangement of trees. Most observed rotational tree fallows occupy well over 50% of time in the tree-crop cycle, a ratio that would be economically unacceptable as a ratio of areas in space. The apparent success of hedgerow intercropping, in which the tree cover is generally below 35%, suggests a greater efficiency for spatial systems. Mechanisms leading to greater efficiency of nutrient recycling under spatial systems would seem to be the cause, but what these are is not known; the answer could lie in the permanence of the tree rooting system.

There is no direct information on this basic question. Research stations should set up controlled trials, in which the effects on soils of the same tree species, management and tree:crop ratio are compared. This is most simply done by planting a rotational fallow adjacent to hedgerow intercropping trials.

Rather than simply alternate trees with crops, the most valuable systems are likely to be those that combine intercropping with rotation. Possibilities of this kind are discussed by Prinz (1986).

Taungya. In the taungya practice, food crops are either grown in rotation with commercial timber trees, or interplanted during the first few years of tree establishment. No-one supposes that this is very desirable as regards soil fertility. Many forestry trees do not leave the soil in good condition after felling, and food crop yields are fairly low. Conversely, it is suspected that annual crops may compete for nutrients with the newly planted trees. In Kenya, under the sequence montane forest, food crops, plantation forestry *(Vitex, Cupressus, Pinus patula, Grevillea)*, soil carbon and phosphorus were substantially lower under the plantation than the forest; it was assumed that the fall in fertility occurred during the cropping period, but no samples were taken at the period needed to test this (Robinson, 1967). Studies of soil changes under plantation forestry are relevant (Lundgren, 1978; Adlard and Johnson, 1983).

The taungya practice appears to be neutral to adverse from a soils viewpoint, becoming seriously undesirable only if substantial erosion is allowed to occur.

Spatial-mixed practices

Trees on cropland. Many kinds of trees are grown on cropland for productive purposes, without having any clear adverse affects on adjacent crops. A small number of species are planted or, more often, preserved in part for their beneficial effect on soils and crop yields, known by farmers and in some cases demonstrated by scientists. Examples and evidence for *Acacia albida, A. Senegal, Paulownia* spp., and *Prosopis cineraria* have been given above. These are spatial-open systems (as compared with the spatial-dense systems such as home gardens). Where such effects occur, it seems logical to augment them by increasing the tree density to something approaching a full canopy, or until light reduction counteracts the improvement in crop growth.

Multistorey tree gardens. Home gardens epitomize the qualities claimed for agroforestry systems. They are highly productive, fully sustainable and very practicable. They are a feature mainly of the humid to moist subhumid tropics (Fernandes and Nair, 1986).

The maintenance of soil fertility is achieved by a combination of inputs, particularly household waste, and a high level of recycling of organic matter and nutrients. The many species present lead to a large litter fall with a range of properties. A large biomass production by bamboos is a common feature. The multi-level root system may be a factor contributing to efficient nutrient recycling.

These features are so obvious that no-one has measured them. A nutrient-cycling study of a home garden would be of interest in showing the magnitudes of nutrient flows and the degree of recycling. With less effort, a comparison of soil properties within home gardens and on adjacent agricultural land could be made. Can home gardens match the degree of closure in nutrient cycling and the physical and chemical soil conditions found under natural vegetation?

Multistorey tree gardens covering wider areas than home gardens are also found. Because of the less intensive inputs, their effects on soils are likely to be less strongly favourable than those of home gardens, comparable with those of plantation crop combinations.

Plantation crop combinations. Combinations of coffee or cacao with *Erythrina, Inga,* and *Cordia* form a widespread agroforestry system in Central America. It is also one of the only two agroforestry practices on which a substantial quantity of soils research exists. These are listed in Table 29.

The main trees included are *Erythrina poeppigiana* and other *Erythrina* species, *Inga jinicuil* and /. *leptoloba,* sometimes with bananas or fruit

Table 29. *Soil studies of plantation-crop combinations.*

Reference	Country	System	Soil aspects
Jimenez & Martinez (1979)	Mexico	*Coffee+Inga,* fruit trees	Biomass
Arangurenetal. (1982)	Venezuela	Coffee+*Erythrina, Inga*	N cycle
		Cacao+*Erythrina, Inga*	N cycle
Bornemizsa (1982)	Colombia	*Coffee+Inga*	Biomass, N cycle
Roskoski(1982)	Mexico	*Coffee+Inga*	N fixation
Roskoski & van Kessel(1982)	Mexico	*Coffee+Inga*	N fixation
Glover & Beer (1986)	Costa Rica	Coffee+*Erythrina*	Biomass, nutrient cycles
		Coffee+*Erythrina,* Cordia	Biomass, nutrient cycles
Russo & Budowski (1986)	Costa Rica	Coffee + *Erythrina*	Biomass, nutrient cycles
Alpizaretal.(1986, 1988)	Costa Rica	Cacao+*Erythrina* Cacao+*Cordia*	Biomass, organic matter, nutrient cycles
Loue(n.d.)	Ivory Coast	*Coffee+Albizia gummifera*	Leaf and soil nutrient differences
Beer (1987)	Latin America	Various	Summary, effects of trees

trees, and *Cordia alliodora.* The plantations may be fertilized. *Erythrina* is usually pruned regularly. *Cordia* is allowed to grow into a mature tree before harvesting for timber. These are usually called 'shade trees', but it is clear that their functions include soil amelioration (Beer, 1987). This role is recognized by farmers. The salient results of these studies are:

1. Large quantities of biomass are returned to the soil, as litter and prunings, both from the coffee/cacao and trees. Values given as kg DM/ha/yr are as follows:

Mexico	Coffee alone Coffee, *Inga* Coffee, *Inga, Musa*	6000 8400-9500 10 200	Jimenez & Martinez (1979)
Colombia	Shade trees	4600-13 100	Bornemisza (1982)
Costa Rica	Coffee, trees trees providing half	16 000-17 000	Glover & Beer (1986)
Costa Rica	*Erythrina* *2* pollardings per year 1 pollarding per year including litter	 11 800 18 500 22 700	Russo & Budowski (1986)
Costa Rica	Cacao *Cordia* Cacao, *Cordia*	7000 10 400 17 400	Alpizaretal. (1986,1988)
Costa Rica	Cacao *Erythrina* Cacao, *Erythrina*	7000 9400 16 400	Alpizaretal. (1986,1988)

2. There is substantial nitrogen fixation by *Erythrina* and *Inga jinicuil,* giving values in kg N/ha/yr fixed of:

Colombia	*Inga jinicuil*	40	Bornemisza (1982)
Mexico	*Inga jinicuil*	47	Roskoski(1982)
Mexico	*Inga jinicuil*	35	Roskoski & van Kessel (1985)

3. There is a large return of nutrients to the soil in litter and prunings, especially but not only nitrogen, giving values in kg/ha/yr of:

		N	K	Ca	
Venezuela	Coffee leaf	28			Arangurenetal. (1982)
	Tree leaf	78			
	Twigs, flowers, fruit	66			
	Coffee + trees	172			

		N	P	K	Ca	
Costa Rica (fertilized)	Coffee	148	8	88	87	Glover & Beer (1986)
	Trees	183	14	74	241	
	Coffee + trees	331	22	162	328	
Costa Rica	*Erythrina poeppigiana*	330	32	156	319	Russo & Budowski(1986)
Costa Rica (fertilized)	Cacao	43	8	30		Alpizar etal. (1986,1988)
	Cordia	71	6	35		
	Cacao, *Cordia*	115	14	65	125	
Costa Rica	Cacao	53	3	27		Alpizar etal. (1986,1988)
	Erythrina	122	7	27		
	Cacao + *Erythrina*	175	9	54	163	

These nutrient returns are sometimes as high as rates of fertilizer application.

The Central American studies do not include monitoring of soil changes over time. It is, however, clearly implied that the soil is maintained in a stable and fertile condition. Aranguren et al. (1982) give values, for depths of 0-20 and 20-30 cm respectively, of 5.3 and 4.1% carbon, which are similar to soils under natural vegetation for this climate.

For six sites in Ivory Coast, Loue (n.d.) compared nutrient contents of coffee leaves and soils for plantations with and without *Albizia gummifera* shade trees. For coffee leaves, the average enrichment for shaded sites was 23% for nitrogen and 16% for phosphorus, whilst potassium showed wide variations. For soils, shaded plantations had slightly higher (non-significant) nitrogen and phosphorus, but were 46% lower in potassium, suggesting that *Albizia* draws potassium from the soil.

For the Central American plantation crop combinations, the following effects of 'shade' trees have been identified (Beer, 1987):

- improvement of drainage and aeration by roots
- provision of mulch
- increase in soil organic matter
- reduction of erosion
- reduction of the rate of soil organic matter decomposition
- recycling of nutrients that are not accessible to crops
- nitrogen fixation
- less need to use chemical herbicides which inhibit beneficial soil organisms.

Spatial zoned practices

*Hedgerow intercropping (alley cropping, barrier hedges).*In hedgerow intercropping, rows of trees or shrubs (the hedgerows) are intercropped with herbaceous crops in the spaces between (the alleys). It is commonly called alley cropping, although this name is less appropriate in that it refers to only one of the two components. Where established on slopes, with the primary objective of erosion control, it may be called barrier hedges, but no clear difference exists between barrier hedges and hedgerow intercropping on slopes. Hedgerow intercropping has aroused more current interest among scientists than any other agroforestry system. Well over half of all diagnosis and design studies have suggested it as an intervention to help solve land-use problems. Among reasons, the potential for maintenance of soil fertility is usually cited.

It is also one of two agroforestry practices on which substantial soils research has been done. Table 30 gives some published studies. Many more will appear as a result of trials recently started or planned. The salient results from these studies are:

1. A large biomass production can be obtained from hedgerows, typically 2000-5000 kg DM/ha/yr in moist subhumid climates, up to 10 000 in humid climates. These values are per hectare of total land in the system.
2. Large amounts of nitrogen can be fixed by hedgerows, e.g. 75 to 120 kg N/ha in six months by *Leucaena* (Mulongoy, 1986).
3. Substantial quantities of nutrients are contained in hedgerow prunings, and can thus be added to the soil if the latter are not harvested, giving values in kg/ha/yr of:

		N		K	
Nigeria	*Leucaena leucocephala*	105	4		Agboola (1982)
	Gliricidia sepium	84	4		
	Tephrosia Candida	118	7		
	Cajanus cajan	151	9		
Nigeria	*Leucaena leucocephala*	200			Kang & Bahiru Duguma (1985)
	Gliricidia sepium	140			
	Acioa barteri	29			
	Alchornea cordifolia	84			
Nigeria	*Gliricidia sepium*	238	14	152	Yamoah et al. (1986a)
	Flemingia congesta	78	8	57	
	Cassia siamea	186	20	100	
Sri Lanka	*Leucaena leucocephala*	105	5	37	Weerakoon & Gunasekera (1985)
Kenya	*Leucaena leucocephala*	196			Bashir Jama et al. (1986)

It is noteworthy that the non-nitrogen-fixing species, *Acioa* and *Alchornea* nevertheless contain substantial nitrogen, as does a species that is probably non-fixing, *Cassia siamea.* Up to 30% of the nitrogen in prunings reaches the crop, the rest being lost by leaching and gaseous losses (Mulongoy, 1986). Thus the likely contribution to crop nitrogen uptake is about 30-80 kg N/ha/yr; using a common rule of thumb of multiplying by 10-15, this factor alone could raise cereal yields by 300-1200 kg/ha.

Residues from prunings of most species used decompose rapidly, with corresponding release of nutrients. There is a corresponding rapid evolution of mineral nitrogen. *Leucaena* has particularly rapid decomposition, releasing 50% of nutrients in the first 25 days.

In many studies, both at Ibadan and elsewhere, there is at least one combination of hedgerow species and spacing in which crop yields are higher than on control plots without hedgerows. The Ibadan trials have consistently achieved this, and it is the case for at least one combination at most sites in a network of seven in different environments in Kenya (EDI, 1987; Amare Getahun, personal communication). This is despite the fact that crop rows close to the hedgerow usually (but not always) show a fall-off in yields.

Table 30. *Soil studies of hedgerow intercropping.*
A. At I IT A, Ibadan, Nigeria.

Reference	Hedgerow species	Soil aspects
Kangetal. (1981,1985)	*Leucaena leucocephala*	Soil changes, crop yields
Agboola(1982)	*Leucaena leucocephala, Gliricidiasepium, Tephrosia Candida, Cajanus cajan*	Biomass, N and P in prunings
Kang&Bahiru Duguma(1985)	*Leucaena leucocephala, Gliricidia sepium, Acioa barteri, Alchornea cordifolia*	N in prunings
Kangetal. (1985)	*Leucaena leucocephala*	Soil changes, crop yields
Mulongoy (1986)	*Leucaena leucocephala*	N fixation, N in prunings, litter decomposition
Sumberg(1986)	*Gliricidia sepium*	Biomass
Wilson etal. (1986)	*Leucaena leucocephala, Gliricidia sepium, Acioa barterii, Alchornea cordifolia*	Nutrients in prunings, crop yields, litter decomposition
Yamoahetal. (1986a)	*Gliricidia sepium, Cassia siamea, Flemingia congesta*	Litter decomposition

Table 30 (cont)

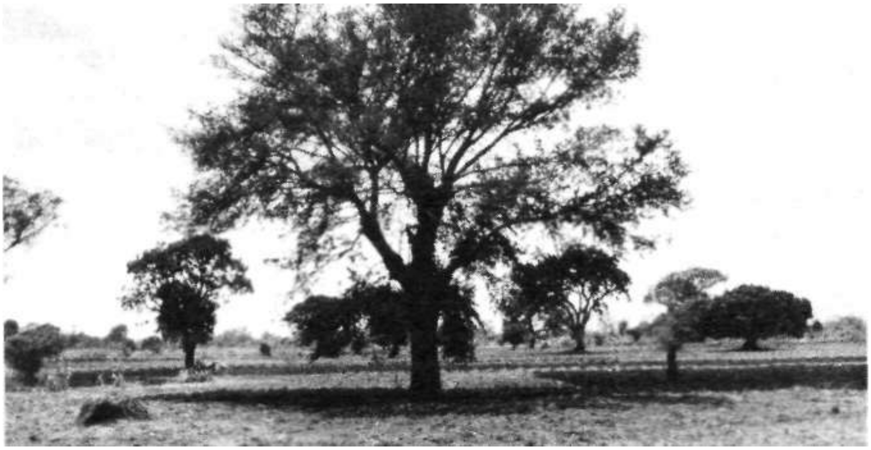
Reference	Hedgerow species	Soil aspects
Yamoahetal. (1986b)	*Gliricidia sepium, Cassia siamea, Flemingia congesta*	Biomass,N,P, Kin prunings, crop yields, roots
Yamoahetal. (1986c)	*Gliricidia sepium, Cassia siamea Flemingia congesta*	Soil changes
Bahiru Duguma et al. (1988)	*Leucaena leucocephala, Gliricidia sepium, Sesbania grandiflora*	Pruning regime effects
Sangingaetal. (1987)	*Leucaena leucocephala*	N fixation

B. At other sites.

Reference	Country	Hedgerow species	Soil aspects
de la Rosa(n.d.)	Philippines	*Leucaena leucocephala*	Crop yields
Weerakoon (1983)	Sri Lanka	*Leucaena leucocephala, Gliricidia maculata*	Biomass, crop yields
Weerakoon & Gunasekera(1985)	Sri Lanka	*Leucaena leucocephala*	Biomass, nutrients in prunings, crop yields, (rice)
Handawela(1986)	Sri Lanka	*Gliricidia maculata*	Soil properties, crop yields
Bashir Jamaetal. (1986)	Kenya	*Leucaena leucocephala*	Biomass, nutrients in prunings, crop yields, soil changes (early stage)
Szottetal. (1987a)	Peru	*Inga edulis* *Erythrina* spp. *Cajanus cajan*	Biomass, soil properties (early (stage)
EDI (1987)	Kenya	Many species	Biomass, crop yield

By contrast, many trials show a decrease in crop yield per unit of total area. This is sometimes compensated by the value (to the farmer or as cash) of the fodder and/or fuelwood produced.

Both increases and decreases in crop yield caused by hedgerows may be due to a variety of factors, microclimatic as well as soil, and no studies have yet appeared which attempt to isolate these. This problem is very complex. A recent discussion, combining soils with other aspects, is given by Huxley (1986b).



15. Trees on cropland: *Acacia albida.* Mangochc, Malawi.

16. Hedgerow intercropping: *Leucaena leucocephala* with intercropped herbaceous legumes in the alleys. Hyderabad, India.

17. Hedgerow intercropping: maize growth after seven years' intercropping with *Gliricidia sepium.* Maha lllppallama, Sri Lanka.

One study has indicated an apparent favourable effect on crop yields of hedgerow root systems, in that maize yields on plots with prunings removed were higher than on controls without hedgerows (Yamoah et al., 1982b).

There have been two studies in which soil changes have been monitored over time, both at Ibadan, Nigeria (moist subhumid bimodal climate). The first consisted of intercropping *Leucaena* with a maize-cowpea rotation (one crop of each per year) on a sandy soil under a moist subhumid climate (Kang et al., 1981, 1985). Soils on plots with prunings applied to the soil were compared with those on plots with hedgerows but with prunings removed (but no data were given for soil changes under crops only). Some results are given in Table 31A. Application of prunings led to higher organic matter, potassium, calcium and magnesium, and substantially improved

Table 31. *Soil changes under hedgerow intercropping (HI), Ibadan, Nigeria.*

A. Leucaenal maize, unfertilized plots, soil depth 0-15 cm (Kangetal., 1981,1985).

Treatment	PH	Ore;anic C	Exchangi; cations (meq/lOOg) K	Ca	Mg	BrayP ppm
Before HI	6.2	0.98	0.25	2.63	1.02	25
After 3 yr HI, primings removed	5.7	0.96	0.16	5.07	0.35	19
After 6 yr HI, prunings removed	6.0	0.65	0.19	2.90	0.35	27
After 3 yr HI, prunings retained	5.7	1.47	0.16	5.33	0.43	22
After 6 yr HI, prunings retained	6.0	1.07	0.28	3.45	0.50	26

B. Cliricidia sepium, Flemingia congesta and Cassia siamea with maize, soil depth 0-15 cm (Yamoah et al, 1986c).

Treatment	Soil changes over 2 years C(%)	N (%)	Bray PI (ppm)	Exchange K (me/lOOg)
Cliricidia				
without prunings	+0.13	-0.019	-33	-0.12
with prunings	+0.17	+0.001	-39	-0.11
Flemingia				
without prunings	-0.56	-0.088	+ 3	-0.29
with prunings	-0.23	+0.023	+22	-0.13
Cassia				
without prunings	+0.15	+0.023	+22	-0.31
with prunings	+0.70	+0.137	+29	-0.22
No hedgerows				
ON	-0.17	+0.039	-21	-0.12
90 N	-0.14	+0.070	-16	-0.15

Species	Soil physical properties after 2 years Bulk density (g/cm^3)	Mean aggregate diameter (mm)	Water content at saturation (%)
Cliricidia	1.26	0.77	39
Flemingia	1.25	0.57	36
Cassia	1.34	0.70	43
No hedgerows	1.53	0.46	35
S.E.	0.05	0.07	1.22

18. Pruned hedgerows of *Leucaena leucocephala* planted between alternate rows of maize. Zomba, Malawi.

19. Multistorey tree garden: coconuts, coffee and bananas on a steep slope. Mindanao, Philippines.

20. Home garden: high production combined with intensive recycling gives full sustainability. North of Hanoi, Vietnam.

the available water capacity. There were no differences in phosphorus. Soil organic matter was maintained over six years, compared with a decline where prunings were removed. These changes in organic matter have been modelled (p. 000). Although the data may not be fully comparable, potassium levels appear to be maintained over time, and calcium levels to rise.

The second Ibadan trial was on a ferric luvisol, 'infertile due to constant use' (Yamoah et al., 1986c). Hedgerows 4 m apart were established with *Gliricidia sepium, Flemingia congesta* and *Cassia siamea*, intercropped with two maize crops over two years. All plots received 60 kg/ha of both phosphorus and potassium; nitrogen treatments ranged from 0 to 90 kg/ha. For each hedgerow species, soil changes were compared with prunings removed and retained, plus a control with no hedgerows. The time period is very short to detect soil changes, and the statistical significance unknown, but there are some intriguing results (Table 3IB). Organic matter decline in the control plot was reversed by *Cassia* and *Gliricidia*, even with prunings removed! The obvious suggestion is root residues. Nitrogen increased in the control, but at nearly twice the rate under *Cassia*, a supposed non-nitrogen-fixing species. Phosphorus improved under *Cassia* and *Flemingia*, but none of the hedgerows checked a decline in potassium. Soil physical properties were significantly better under all species than without hedgerows. The authors several times single out the favourable effects of 'the abundant and persistent mulch from the *Cassia'.*

Other data are fragmentary. In the subhumid zone of Sri Lanka, under an intercropping system with *Gliricidia maculata* at 5 m by 1 m, soil organic matter and nitrogen were better than on a control plot with maize only, and soil structure better (compressive strength lower) (Handawela, 1986). At Maha Illuppallama, Sri Lanka (moist subhumid climate), *Gliricidia sepium* intercropping plots are maintaining nitrogen levels but apparently, after a few years, encountering phosphorus deficiency (L. Weerakoon, personal communication). On the Kenya coast, early-stage results suggest *i* an increase in carbon, phosphorus, potassium and calcium (Bashir Jama .etal., 1987).

Reasons for supposing that hedgerow-intercropping systems can be designed which effectively control erosion, and thereby loss of nutrients in eroded soil, are discussed in Part II.

Hedgerow intercropping presents many problems, not least those associated with the long tree-crop interface, the highest in any kind of agroforestry other than spatial dense practices (Young, in press, b). If hedgerows are 1-m wide and cropped alleys 4-m, the interface is 4000 m per hectare. If soil, microclimatic or other interface effects are, on balance, favourable, then this is a good thing. If they are adverse in net effect, then hedgerow intercropping is unlikely to be successful. For the soil-based interactions alone, the above-ground effects are likely to be favourable to the crops, through nutrient additions from litter. Below-ground effects could be beneficial, through addition of organic matter and nutrients in root residues, or adverse, through hedgerow competition with crops for nutrients. Little is known about these effects.

Favourable effects on crop yields are most likely to occur in systems in which hedgerow prunings are applied to the soil. If they are harvested, effects will necessarily be much smaller, although roots may provide some benefits.

Most trials to date have been in humid to moist subhumid climates. However, performance in recently commenced trials in the dry subhumid zone, such as at ICRISAT (Hyderabad, India) and ICRAF (Machakos, Kenya), is not unfavourable.

Where hedgerow intercropping is established on slopes, it may be called a system of barrier hedges. In such cases there is a close integration of erosion control and fertility maintenance; erosion control is achieved in part by the litter cover of prunings, which contribute also to fertility.

HEDGEROW INTERCROPPING AND SOIL FERTILITY

Systems of hedgerow intercropping appear to have the capacity to maintain soil fertility, with low to moderate inputs, where the tree component occupies only 15-25% of the land.

This contrasts with systems of rotational fallow, in which the tree component normally occupies more than 50% of the rotation.

If this comparison is confirmed, it suggests that hedgerow intercropping is more efficient in its use of land and offers an alternative to shifting cultivation.

The processes by which this effect is achieved are not fully understood. Research into these processes will help support the design of sustainable systems for different conditions of climate, soil and slope.

Despite the fragmentary nature of the data, the hypothesis that hedgerow-intercropping systems can be designed to maintain soil fertility as well as being productive remains a distinct possibility. If proven, these systems could make a very large contribution to sustainable agriculture in the tropics, both on sloping lands and on soils with low or declining fertility.

Boundary planting. Because of the relatively short tree-crop interface, effects on soils are likely to be small, and could be positive, neutral or negative. This is the kind of spatial arrangement in which to plant trees which are wanted for production but may be adverse to soil conditions.

Trees on erosion-control structures. The spatial arrangements and functions of trees and shrubs for control of soil erosion have been discussed in Part II of this review. There are many opportunities for combining erosion control, which in itself is a means of maintaining fertility, with the other beneficial effects of trees.

For trees planted on grass barrier strips, bunds and terraces, the contribution to soils from tree litter is likely to be small but positive. *Grevillea robusta, Cassia siamea* and *Leucaena* are commonly employed in this way.

Windbreaks and shelterbelts. Whilst intended primarily to control wind erosion, there is an apparent potential to make use of the soil fertility effects of trees in this practice—the spreading of leaf litter on crops being achieved by the wind! Modern practice is to design windbreaks of several tree and shrub species with differing shapes, which gives opportunity deliberately to include some of the known soil-improving species that occur in semi-arid areas, such as *Acacia albida,* other acacia species, *Prosopis cineraria* and *Azadirachta indica.* It appears possible, through imaginative design of windbreaks, to achieve erosion control, microclimatic amelioration and improved soil fertility, a combination of high potential value to the semi-arid zone.

Biomass transfer. This refers to the practice, found for example in Nepal, of cutting tree foliage from natural forest and carrying it onto cropland. Doubtless it improves yields, or farmers would not undertake the enormous labour involved. If associated with cutting for fuelwood, there is likely to be degradation of forests.

Sylvopastoral practices

Trees on rangelands or pastures. Trees and shrubs contribute to sylvopastoral systems by direct provision of leaf fodder and through improvement of pasture growth beneath them. The effect on pastures can arise from many causes, including microclimatic amelioration and the effects of animals (domestic or wild) and birds, but it certainly includes an element of soil improvement.

Those trees which benefit crop yields, such as *Acacia albida* and *Prosopis cineraria,* have an equal, or probably greater, effect on pastures. Acacias in general appear to improve pastures, at least partly through nitrogen fixation. Evidence is provided by tree-soil transects under natural vegetation (p. 93). Relevant in this respect is the finding that, within certain rainfall limits, the productivity of Sahelian pastures is limited not by water, but by the availability of nitrogen and phosphorus (Penning de Vries and Krul, 1980).

The *dehesa* system of Spain and adjacent Mediterranean countries demonstrates complex interactions between trees, pastures, livestock and soils. Oaks *(Quercus rotundifolia* and other *Quercus* spp.) grow on rangelands, which arc grazed by cattle, sheep, goats and pigs. There may be recurrent cereal cropping. Under oak canopies, both soil conditions and pasture growth are substantially better. Thus in Sevilla, Spain, soil organic matter, nitrogen, phosphorus and potassium were found to be about twice as high under trees than in adjacent pasture, nitrogen-mineralization higher, and calcium and magnesium 1.5 times as high (Joffre et al., 1988).

Such improvements in soils and pasture growth can be promoted through management only if there is opportunity to promote cover by selected tree species, either by planting or protection of natural seedlings against browsing of the growing shoot. Agroforestry in rangelands is unlikely to be successful unless applied in conjunction with basic principles of pasture management, such as control of livestock numbers and rotational grazing. Given socio-economic circumstances which allow such management, there is a clear potential for soil improvement through the use of trees.

Other sylvopastoral practices. Combinations of plantation crops with pastures, such as grazing under coconuts, are adopted primarily for purposes other than soil improvement, although a grass-legume ground cover can contribute to growth of the plantation tree through nitrogen fixation and recycling. The practices of live fences and fodder banks have no direct implications for soil fertility.

Practices with the tree component predominant

Woodlots with multipurpose management. This practice refers to planted forests which are managed with the intention of multiple production, for example forest grazing or tree fodder, possibly at the cost of not maximizing wood production. There is often an element of conservation in such areas, and the planting of trees which are desirable from the point of view of soil fertility should be among the aspects taken into account in design.

Reclamation forestry leading to multiple use. Like multipurpose windbreaks, this is another area of which the potential has been little explored. Reclamation forestry is a known and successful means of restoring areas of degraded soils, through the effects of the forest litter cover in checking erosion and building up soil organic matter and nutrient status.

There are opportunities to combine such reclamation with productive agroforestry, by a two-stage approach. In Stage I, reclamation, a complete forest cover is established and protected. In Stage II, controlled production with protection, management is modified in such a way as to maintain a sufficient degree of conservation but permit controlled production. The latter might include any combination of fuelwood, grazing, cut-and-carry grass or tree fodder, or even limited cultivation. Management measures to achieve this could consist of either a thinning of the tree cover or a selective clearance along contour-aligned strips. Such systems might be designed for reclamation of eroded soils, saline soils or sand dunes. Some of the trees planted for the reclamation stage could be selected with a view to their functions in the productive stage, for example nitrogen-fixing species which improved pasture growth. Examples have been noted above (p. 74).

Practices with special components

In *aquaforestry*, the effects on soils are highly specialized. A known system is the planting of trees, for example *Sesbania* spp., around borders of fishponds, with reported benefits to nutrient content of the water and therefore nutrition of fish. In combinations of mangroves with fishing there could be some comparable effects. The practice of *entomoforestry* (trees with insects, e.g. bees, silkworms, butterflies) has no direct implications for soils.

Summary: effects of agroforestry practices on soil fertility

A tentative grouping of agroforestry practices according to their effects on soil fertility is given in Table 32. There is clear scientific evidence for beneficial effects upon soils of some systems of *trees on cropland* and *plantation crop combinations.* Although lacking evidence of this kind, there is no doubt that *home gardens* maintain soil fertility. The labour input of farmers attests the effectiveness of *biomass transfer* as a method of fertilization.

Table 32. *Agroforestry practices in relation to soil fertility.*

Practices with substantial positive effects on soil fertility
- Improved tree fallow
- Trees on cropland
- Plantation crop combinations
- Home gardens
- Hedgerow intercropping
- Trees on erosion-control structures
- Windbreaks and shelterbelts
- Biomass transfer
- Trees on rangeland or pastures
- Woodlots with multipurpose management
- Reclamation forestry leading to multiple use

Practices with smaller positive or neutral effects on soil fertility
- Boundary planting
- Plantation crops with pastures

Practices with positive or negative effects on soil fertility
- Shifting cultivation

Practices with neutral or negative effects on soil fertility
- Taungya

The limited available results suggest that, for a range of environments, it is possible to design systems of *hedgerow intercropping* which maintain soil fertility. Given that this is a new practice, further evidence, from nutrient-cycling studies and soil monitoring, is needed before this can be taken as proven.

For the practice of *trees on erosion-control structures,* large improvements to soil fertility arise from the reduction in losses of organic matter and nutrients attributed to erosion control; the trees have a supplementary effect through addition of litter. The same combination of a large fertility effect through wind-erosion control with potential for further improvement by tree litter applies to *windbreaks and shelterbelts.*

For *trees on rangeland or pastures,* there is clear evidence that some trees promote pasture growth beneath them and that this leads to, or is associated with, improved soil fertility. For this to occur, it must be associated with good pasture management.

The adaption of *woodlots* and *reclamation forestry* into agroforestry through management for multiple use carries with it the known beneficial effects of a forest cover, given appropriate tree species and good management.

Improved tree fallow could have benefits similar to or greater than natural fallow in shifting cultivation, but there is no experimental evidence.

Design, management and integration

> Labourer: 'And as we reaped, we used to sing.'
>
> Interviewer (eagerly): "What songs did you sing?"
>
> Labourer: 'Songs don't matter. It were the singin' as counted.'
>
> Interview between an elderly English farm labourer and an enthusiastic young sociologist, concerning conditions around 1900.

As in all branches of agriculture and forestry, sound design and good management of an agroforestry system matter as much or more than the nature of the practice itself. The presence of trees does not necessarily control erosion nor maintain soil fertility; what matters is the way they are arranged and managed.

This applies with greatest force to practices that are new. It is certainly possible to conceive of a hedgerow-intercropping system which depresses crop production, fails to provide compensating products from the hedgerows, and neither controls soil erosion nor sustains fertility.

For any projected intervention of agroforestry into an existing land-use system, sound design is the first essential. The detailed techniques set out in the design stage of agroforestry diagnosis and design are intended for this purpose (Huxley and Wood. 1984; Raintree, 1987). Plant selection and system design in relation to local conditions of climate, soil and slope are important aspects. Specifically from a soil-fertility aspect, consideration must be given to which parts of the trees and crops are harvested and which returned to the soil, with production being balanced against soil amelioration. The second essential is that the system should be well managed, both from the basic aspect of maintenance and as regards flexible adaptation if failing performance indicates a need for change.

Agroforestry should not be treated in isolation, but as an element in land-use planning as a whole (Young, 1987c). At the farm level, examples of imaginative integration are the approaches called conservation farming in Sri Lanka and integrated land use in Malawi. In conservation farming in Sri Lanka, elements include mulching, minimum tillage, measures for pest control and agroforestry. In Malawi, trees are being introduced into farming systems gradually, with an initial emphasis on planting on marker ridges and other soil-conservation structures (Weerakoon, 1983; Wijewardene and Waidyanatha, 1984; Douglas, 1988).

Opportunities for including agroforestry along with other kinds of land use in integrated watershed management have been noted above (p. 75). Agroforestry can best achieve its potential, for soil conservation as for other purposes, where it is considered together with other major kinds of land use as an element in land-use planning.

Part IV. Agroforestry for Soil Conservation

Chapter 15
Modelling Soil Changes under Agroforestry

Objectives

It is clearly desirable to be able to predict how soil properties will change under specified agroforestry systems on a given site, and to be able to compare these with changes under other land-use systems, existing or proposed. If this could be done, then we should possess a valuable technique for evaluating proposed systems in terms of environmental impact, to be used alongside evaluation in economic and social terms.

There is a further need to estimate impact on soil in the design of agroforestry research. An agroforestry field trial takes five years or more to obtain useful results. Any possible aid that might help in its design is therefore welcome. Furthermore, no field trial can include all possible combinations of variables; once some field data have been obtained, it would be useful to be able to extend these to estimates of the impact on soils of designs that have not been tried, e.g. 'Suppose we had removed the crop residues and not retained them, would this system still be sustainable?'

Predictions require data, and nothing is more demanding of quantitative data than a computer model. It draws attention to any critical elements that are required in order to predict soil changes, and indicates how important it is that particular items of data are accurately obtained—in technical terms, the sensitivity of the model to particular variables. Modelling can therefore help field research scientists by indicating the data that are required if predictions of changes in soil fertility are to be made.

It should be emphasized that present knowledge of soil-plant processes is insufficient to be able to make such predictions with confidence. Besides the need for more experimental studies, we require a better understanding of some of the basic soil processes involved. By comparing model outputs for different data and assumptions, for example different values of the tree-proportionality factor in erosion or the humus-decomposition constant, we can see what advances in basic knowledge are needed if predictions are to be made with greater confidence.

It was with these needs in mind that a computer model was constructed, Soil Changes Under Agroforestry or SCUAF (Young and Muraya, in press,a,b). Its primary aim is to predict the effects upon the soil of specified agroforestry systems within given environmental conditions. In more detail, the objectives of the model are:

1. To make approximate predictions of the effects upon the soil of specified agroforestry systems within given environments.
2. To show what data are needed from agroforestry experimental work if such predictions are to be made.
3. To make use of these predictions as a tool in the design of agroforestry systems, either for selecting the most promising systems for initial trials or for improving systems for which some data on performance are available.
4. To indicate what advances in knowledge of plant/soil and soil processes are needed in order to improve the accuracy of such predictions.

OBJECTIVES OF THE SCUAF MODEL

- to predict the effects on soils of specified agroforestry systems in given environments
- to show what data are needed to make such predictions
- to use predictions in the design of systems for agroforestry research
- to indicate what advances in knowledge are needed in order to improve the accuracy of the predictions.

The SCUAF model is only described in outline here, with illustrations of some results. A detailed account of the basis and functioning of the model, which covers erosion, soil organic matter and nitrogen cycling, together with instructions for users, is given in Young and Muraya (in press, b). The model is available on diskette.

Basis of the model

Models exist for the prediction of soil erosion and for nutrient cycling, particularly nitrogen, under agricultural systems. Many of these are of considerable complexity. What is needed for the present purposes is a model which, first, is relatively simple, so that it can be used by people other than its designer and, second, is focussed on the specific situation in agroforestry.

The first need was met by constructing an input-output model, rather than one in which there is sophisticated modelling of processes. For the second, the essential basis is to have two plant components, tree and crop, which can be present either in a rotation or in a spatial system.

It is clearly desirable to include prediction of soil erosion, not only mass of soil lost but also its content of organic matter and nutrients. Next in importance is prediction of changes in soil organic matter, on the grounds of its multiple role in soil fertility, with respect to soil physical conditions and also because organic matter is itself a source of plant nutrients. Thirdly, the model should include cycling of the major nutrients, particularly nitrogen in view of the role of nitrogen-fixing trees, and phosphorus as the other nutrient which is most often a check to sustainability.

There is one important factor omitted from the present model, that of soil water. In dry savanna and semi-arid environments this is frequently the limiting factor to plant growth, and it is hoped to incorporate it in future development of the SCUAF model.

A year-by-year time basis was chosen, again in the interests of simplicity; this contrasts with modelling on short time periods, such as 10 days, in some process-simulation models. On sites with two growing seasons in a year, either the plant growth can be summed for both seasons or each season treated as if it were a 'year' in the model. Initial soil conditions and plant growth are input, and changes to the soil predicted for the first year; the effect of these changes on plant growth in the second year is then estimated, and used to predict further soil changes. This iterative cycle can be continued for as long as desired but with progressively decreasing confidence. For the prediction of sustainability, a 20-year period provides a good basis; the soundest application is to take experimental results for some three to five years and extrapolate these for a longer period.

A set of default values is included. In using published results as a means of validating the model, it was almost invariably found that some items of data were missing, most frequently information on roots. Best estimates had therefore to be supplied. In using the model for demonstration and training purposes, many items are not readily accessible. The model contains default values for all items, the values of which are set by the input of climatic zone, soil texture class and slope class. For example, if the user inputs a lowland humid climate and a medium-textured soil, the model sets values, such as initial soil carbon and rates of plant growth, that arc typical of that environment. Estimates of the factors in the universal soil loss equation are set on the basis of slope, climate and soil. *All* default values are presented on the computer screen to users, who have the opportunity to change them—and should substitute observed data wherever possible.

A particular case is presented by soil processes. Much agroforestry research is conducted by scientists who are not soil specialists, and not in a position to estimate values such as litter-to-humus decomposition conversion ratios or humus decomposition constants. Best estimates of all such process constants have therefore been compiled from published specialized studies.

The model was calibrated by taking studies of natural ecosystems in different climates, assuming that the soil was in a steady state, and from published accounts of agriculture, forestry and the small number of soil studies of agroforestry systems.

Structure of the SCUAF model

The SCUAF model can be thought of as consisting of two compartments, a plant compartment and a soil compartment. The plant compartment treats what happens to the plant material—trees and crops—before it reaches the soil. It is essentially the same for both carbon and nutrient cycling. The soil compartment models what happens in the soil, taking as one of its inputs, outputs from the plant compartment. Modelling of erosion is a distinct subunit of the soil compartment.

The plant compartment

The plant compartment is included in the carbon model shown in Figures 16 and 17, the former in simplified form. In any agroforestry system there are two plant components, called TREE and CROP (where CROP can be pasture). The TREE is partitioned into four parts, LEAF (herbaceous matter), FRUIT (reproductive matter), WOOD and ROOT. The CROP will usually contain only LEAF, FRUIT and ROOT, but the possibility of including a WOOD component is included in order to cover cases such as coffee (CROP) beneath shade trees (TREE). The source of carbon for plant growth is the atmosphere, through the process of photosynthesis. The user is asked to input the initial rates of net primary production of each plant component, partitioned into its parts.

For the carbon cycle, the values for dry matter given as net primary production are converted to carbon, taken by default as 50%. For the nutrient cycles, estimates are required of the nutrient content of each plant part, as fresh leaves in the case of prunings but at the time of shedding in the case of natural litter.

The user next specifies the *agroforestry system,* as spatial or rotational. If spatial, the percentages of land under tree and crop components (which can add up to more than 100%) are entered. If rotational, the user is asked how many years are under crops and under trees. In some agroforestry systems, the tree component is allowed to grow for a number of years, after which it is cut in some way, e,g. coppiced, pollarded or felled; this is called a *cutyear.* Where there is annual pruning, the cutyear is entered as one.

Some of the plant parts will be removed from the system as harvest or, in some systems, browse or burning. CROP FRUIT, the main food harvest, will always be removed, whereas CROP LEAF, the crop residues, may or may not be harvested. There may be an additional harvest in the cutyear,

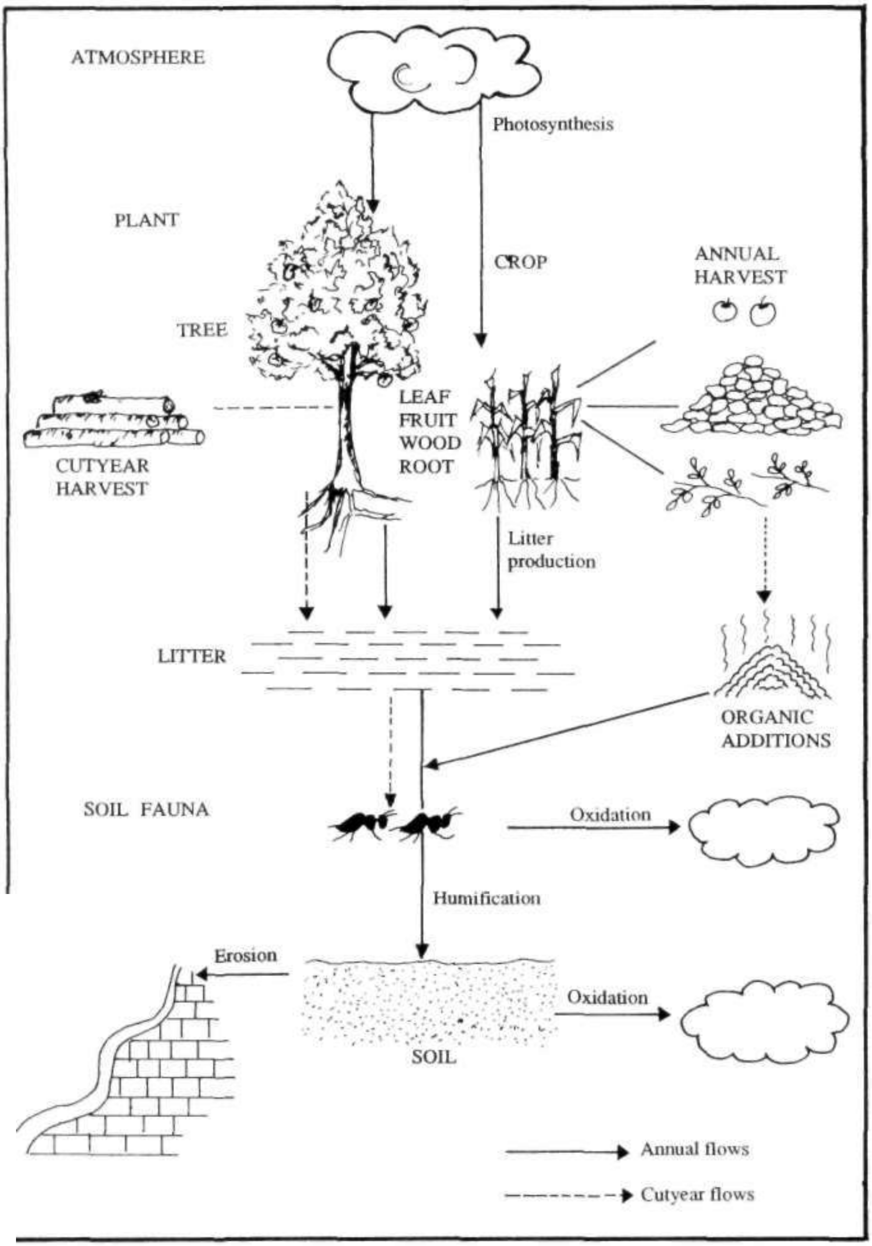


Figure 16. Outline of the SCUAF carbon cycle model, simplified.

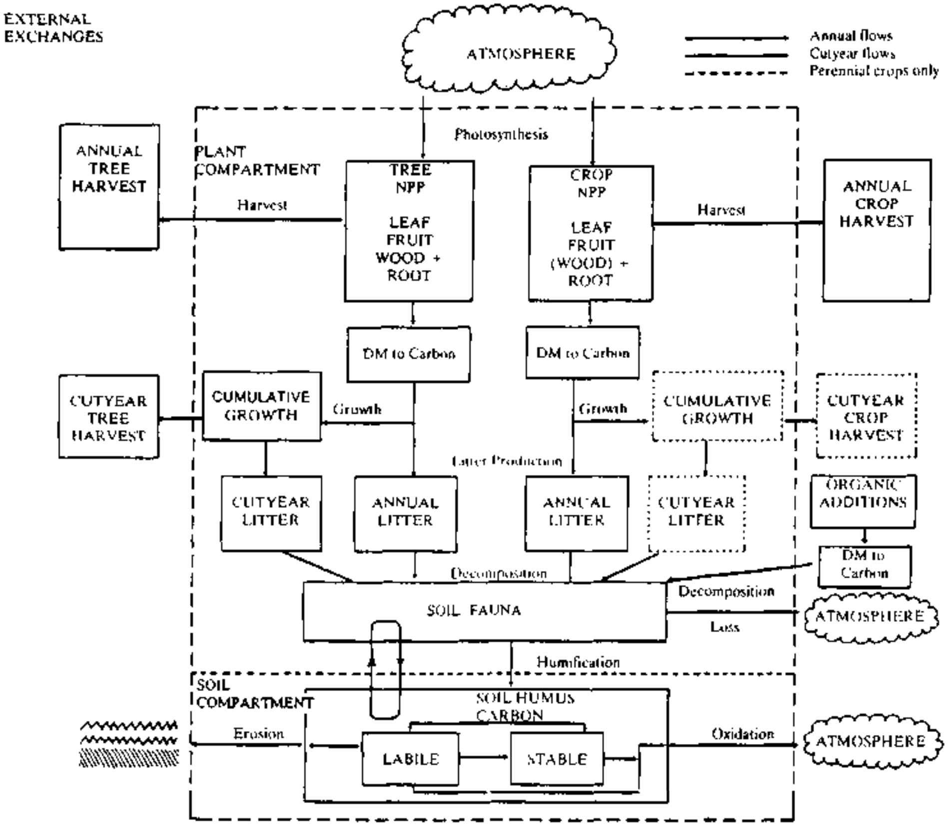


Figure 17. Structure of the SCUAF carbon model.

particularly of TREE WOOD, as timber or fuelwood. In some systems there arc ORGANIC ADDITIONS originating outside the system, such as compost or manure. Some of the harvest may have been fed to livestock, and farmyard manure returned; this can be included in the model—but the transfer must be made by hand!

Out of these nine plant components (two plants, each with four parts, plus organic additions), what is not harvested or otherwise lost becomes LITTER, which includes prunings and root residues. The output of LITTER from the plant compartment, with its content of carbon and nutrients, becomes an input to the soil compartment.

Erosion

Soil erosion is calculated from the equation:

Erosion (kg/ha/yr) = R x K x S x C x 1000
where R = climate factor
K= soil erodibility factor
S = slope factor (LS in the USLE)
C = cover factor.

In each case, the factors may be obtained either by the simplified methods given in the FAO system (intended for use in estimating average erosion over large areas) or, where data permit, by the more sophisticated methods given in the USLE (intended for estimating erosion on individual farm fields).

When these factors have been entered, the model calculates values of erosion separately for the tree and crop components, and displays them. For rotational agroforestry systems, these values are used in the respective years under the tree or crop components. For spatial systems, the user enters the tree-proportionality factor. The model then displays the calculated rate of erosion for the system as a whole. The calculated values both for the tree and crop components alone and for a combined spatial system can be over-ridden by entering measured rates of erosion.

Having obtained erosion as kilogrammes of soil per hectare per year, losses of carbon and nutrients are calculated, together with reduction in soil profile depth. For carbon and nutrients, the proportions present in the original topsoil are multiplied by enrichment factors for eroded sediment (p. 45). For example, erosion of 5000 kg/ha/yr from a topsoil with 0.1% nitrogen and a nitrogen-enrichment factor of 4.0 would produce a loss of 5000 x 0.001 x 4.0 = 20 kg N/ha/yr. Change of profile depth is calculated from dry bulk density.

This gives erosion of soil, carbon and nutrients for the initial year. For subsequent years, climate and slope will remain the same but the soil and cover factors will be modified, with increase or decrease in soil organic matter and in plant growth. These are calculated in year-by-year iterative fashion.

Soil humus carbon

The annual balance of soil humus carbon, C, is given by:

$$C_{t+1} = C_t + \text{additions} - \text{oxidation} - \text{erosion}$$

where t and t+1 are successive years, additions are from humification of litter, oxidation is loss of CO_2 by soil fauna and erosion is loss of carbon in eroded soil.

Additions are calculated from the material in the various plant parts which become litter, multiplied by the litter-to-humus conversion losses for above-ground and root residues. This includes all plant carbon that is oxidized in less than one year, and is thus a large loss. The lack of information on its value for different circumstances is the greatest uncertainty in the carbon submodel.

Loss by oxidation is based on the decomposition constant (p. 108). The user may specify either one or two humus fractions, the latter called labile and stable, with stable humus having a considerably slower rate of decomposition. The equations employed for one- and two-fraction oxidation losses are given on pp. 108 and 111. The user can choose which depth of soil profile to include for carbon cycling. For the non-soil specialist, the working assumption for general agroforestry research proposed above is recommended, namely to select the topsoil only (15 or 20 cm), and to assume that most of the humus contained in it belongs to the labile fraction, i.e. to assume one humus fraction.

Soil fauna are included as an agent in processes, being responsible both for litter conversion loss and humus oxidation. As the carbon within their biomass is relatively small, however, it is not separately determined.

The carbon-cycling submodel is based essentially on the descriptive analysis made by Nye and Greenland (1960), adapted to permit two humus fractions. Thus modified, it is notably similar (although independently constructed) to the carbon section of the CENTURY model of Parton et al. (1987), where CENTURY'S plant carbon, active soil carbon, slow soil carbon and passive soil carbon are SCUAF's litter, soil fauna, labile humus and stable humus respectively.

Nutrient cycling

The nutrient cycles in SCUAF consist of input-output modelling of the cycles shown in Figure 12, with the gains and losses from the soil as listed on p. 133. For each nutrient, there is a soil input consisting of the nutrients reaching the store of litter.

For the nitrogen cycles, the user states, when specifying the agroforestry system, what proportions of the tree and crop components are nitrogen fixing and how much nitrogen would be symbiotically fixed by a pure stand of the nitrogen-fixing components (see Table 22). Nitrogen fixing of the system as a whole is then calculated proportionally to time or space occupied. Loss of nitrogen by erosion is calculated as noted above. Fertilizer added is entered, and gains from atmospheric deposition and non-symbiotic fixation estimated.

The pool of available mineral nitrogen is calculated and partitioned between gaseous losses, fixation on clay minerals, leaching, erosion and plant uptake. The total nitrogen available to plants is the sum of uptake *from* the soil mineral pool plus that obtained directly by symbiotic fixation. It will be apparent that there are some large uncertainties (as in all other nitrogen-cycling models), notably the loss through leaching, data on which can only be obtained by lysimeter studies. Default values for climate and soil texture are included, obtained by review of publications.

The phosphorus cycle is similar, except that input from weathering of rock minerals is substituted for atmospheric fixation; losses by fixation onto clay minerals are relatively more important, with default values dependent on soil acidity. The difficulty in measuring or estimating nutrient inputs from rock weathering adds a further element of uncertainty.

There is an argument that if a process cannot be measured, or estimated with reasonable confidence, then it should not be employed in calculations. If this is accepted, then nutrient cycling cannot yet be modelled. The view taken in the SCUAF model is that it is better to set best estimates, however uncertain, as default values than to omit some processes altogether.

Feedback effects of soil changes on plant growth

The rates of tree and crop growth input to the model are those under initial soil conditions. As the soil properties change, the growth of plants will be affected. This is modelled by means of feedback factors, operating within the annual time cycle of modelling. There are feedback factors for soil carbon, nutrients and soil depth.

The basis for each feedback factor is that a change in a soil property, relative to its initial conditions, produces some proportional change in plant growth. For example, if the carbon feedback factor for trees is set at 0.5, a 1% relative fall in soil carbon (e.g. 10 000 to 9900 kg C/ha) produces an 0.5% reduction in the rate of tree growth. With all feedback factors set to 0.0, rates of plant growth remain constant. Thus:

$$NPP_t = NPP_0 \times (1 + (((C_t - C_0)/C_0) \times CFF))$$

where NPP_0 and NPP_t are net primary production initially and in year t respectively, C_0 and C_t are soil carbon initially and in year t, and CFF is a carbon feedback factor.

Feedback factors are given separately for trees and crops, and for carbon, nitrogen, phosphorus and soil depth. For the nutrients, feedback is based not on the organic reserves but on those in available mineral form. Default values are set at 1.0 for crops and 0,5 for trees, but the user should adjust these. Data from fertilizer trials may be employed (adjusted for the proportion of fertilizer nutrients reaching the plant). This is another case of the preference for a highly uncertain estimate to none at all—which would be equivalent to assuming that plant growth is unaffected by soil!

In practice, the feedback for loss of soil profile depth is almost always found to be negligible compared with that for loss of organic matter and nutrients, showing the invalidity of early attempts to calculate effects of erosion on productivity in terms of soil depth.

The SCUAF menu

Figure 18 gives a user's view of the SCUAF menu. There are three submenus, for inputs, outputs and utilities. The first input is to select which cycles are to be included: carbon, nitrogen or phosphorus, singly or in combination; in every case, erosion is included. Documentation sets a title, file name and other identification data. The spatial or rotational details of the agroforestry system are set, together with additions (organic or fertilizer) and removals (harvest or other losses). The initial conditions cover soil, erosion (factors or rate) and plant growth (tree and crop, partitioned into parts). The parameters in soil processes and the soil-plant feedback factors are then entered.

Apart from screen displays or printouts of the documentation and data, outputs consist of changes, over any specified period of years, in erosion (and its causative factors), soil humus carbon (one or two fractions), nitrogen, phosphorus, plant biomass production as affected by soil, total soil-plant system biomass anci carbon, and harvest. The changes estimated for plant biomass production (growth) refer only to the effects of soil changes, not to the many other influences which affect plant growth. Harvest is a selection from the plant growth values of those items indicated as harvest, e.g. crop fruit, crop leaf (fodder) and tree wood (fuelwood).

Output is initially in the form of tables. A link to a commercial software package permits automatic production as graphs. The utilities menu allows a set of data to be stored, and subsequently retrieved.

All inputs and outputs operate independently. The user can therefore input a set of conditions and obtain outputs, or return to the input menu and change one or more values and obtain further outputs with all other values unchanged. This allows rapid comparison of conditions, e.g. 'What would be the effect if we could find a tree with 10% faster growth, or reduced the proportion of land under trees?'

Comparison with agricultural land-use systems can be achieved by using identical input data, but specifying an 'agroforestry system' consisting of 0% tree and 100% crops. Reversing these proportions allows the model to be used for reclamation forestry.

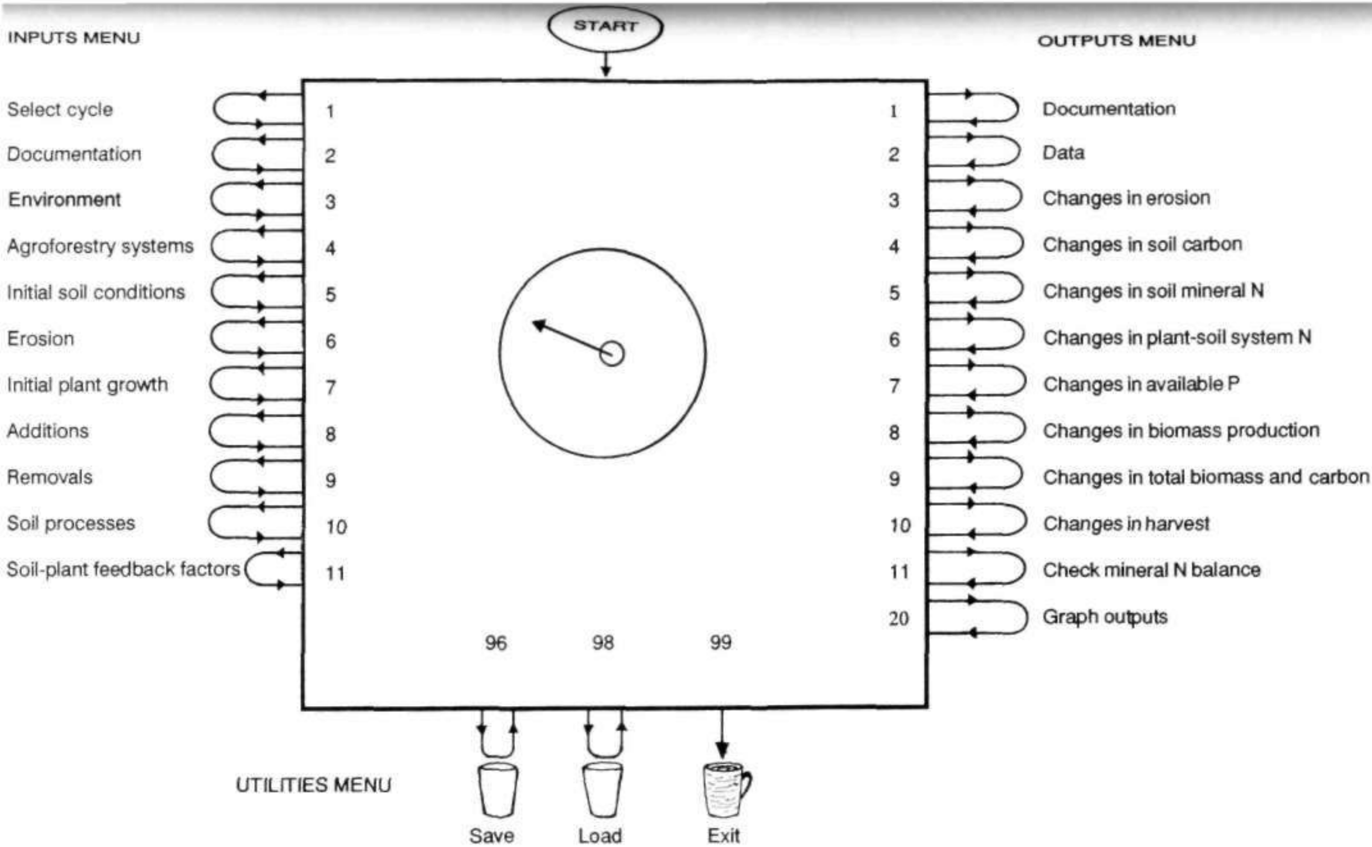


Figure 18. User's view of the SCUAF menu.

Examples

To illustrate the outputs from the SCUAF model, five examples are given, taken from rotational, spatial zoned and spatial mixed agroforestry systems. Other examples will be found in Young et al. (1987) and Cheatle et al. (1989).

Shifting cultivation is the only rotational agroforestry system for which there are data available (Figure 19). In a study some years ago in the Philippines, there was an average of three years' cultivation followed by 15 years' fallow (an R factor of 16.6%), under which it was implied that the system was sustainable (Kellman, 1969). The climate is lowland humid, and much land is steeply sloping. Erosion rates had been measured. The modelling of changes in soil carbon is given by the upper line in Figure 19. Decline during the period of cultivation is balanced by a rise during the forest fallow, with a 'jump' caused by inputs of root residues upon clearance. Also shown in the figure are the simulated effects of shortening the fallow to 11 and 7 years, leading to a soil-degrading system.

Figure 20 shows changes in erosion for a shifting cultivation system in which the fallow has been reduced to three years; data are simulated. The abruptness of the changes between cropping and fallow periods is not wholly realistic. Erosion increases for each year that the cropping period is continued; it is also greater at each successive return to the same point in the crop-fallow cycle, as a consequence of progressive soil degradation.

Figure 21 is based on a study of *Leucaena-maize* hedgerow intercropping at Ibadan, Nigeria, in which soil changes were measured after six years. The climate is lowland subhumid bimodal and the soil is sandy. The two upper lines are for plots with *Leucaena* prunings retained, the lower ones where these were removed, in both cases for unfertilized treatments. The circles are the observed soil carbon values. Using a decomposition constant of 4%, predicted soil carbon with the prunings retained rises to 18 000 kg/ha, above the observed value. A correct prediction is achieved by raising the decomposition constant to 6%. The considerable loss of carbon where prunings are removed (but crop residues retained) can only be simulated by a decomposition constant of 11%. These values are not unrealistic, however, since it is known that oxidation of humus is more rapid on sandy soils (Parton et al., 1987), and removal of prunings would leave the soil unprotected from the very high soil surface temperatures recorded at this site.

Figure 22 illustrates a spatial, mixed agroforestry system, the combination of cacao with *Cordia alliodora* (Alpizar et al., 1986, 1988). The climate is lowland humid (altitude 600 m, rainfall 2600 mm with no dry months) and the soil strongly acid, with quite high organic matter (topsoil carbon 2.5%). There is a fertilizer input of 120 kg N/ha/yr. Data for soil changes over time are not given, but it is implied that properties are stable, and explicitly stated to be so for nitrogen. In modelling, cacao is treated as the crop component. Using default values for soil processes, modelling shows a slow decline in organic carbon, which is restored if it is assumed that the *Cordia* are cut after 15 years and root residues enter the soil; in practice, there may be continuous, dispersed cutting. For nitrogen cycling, the data show an apparent gain to the soil (per hectare, per year) of 12 kg nitrogen and 13 kg phosphorus, and a loss of 50 kg potassium.

The last example illustrates the use of SCUAF in experimental design. In Figure 23, the initial data are taken from a study of maize monoculture on erosion plots in Ivory Coast, extrapolated by modelling to 10 years. The system is clearly degrading. After 10 years, this is replaced by a simulated agroforestry system, leaving all variables unchanged other than those affected by the introduction of a tree component. The major effect is a large reduction in erosion, which would probably take two to three years to achieve. With a proportion of trees typical of hedgerow intercropping, 20% or less, the system is still not fully sustainable. If the trees cover 40% of the land, there is a recovery in soil organic matter. This leads to the question of whether an agroforestry system can be designed with this proportion of trees which meets other criteria of acceptability.

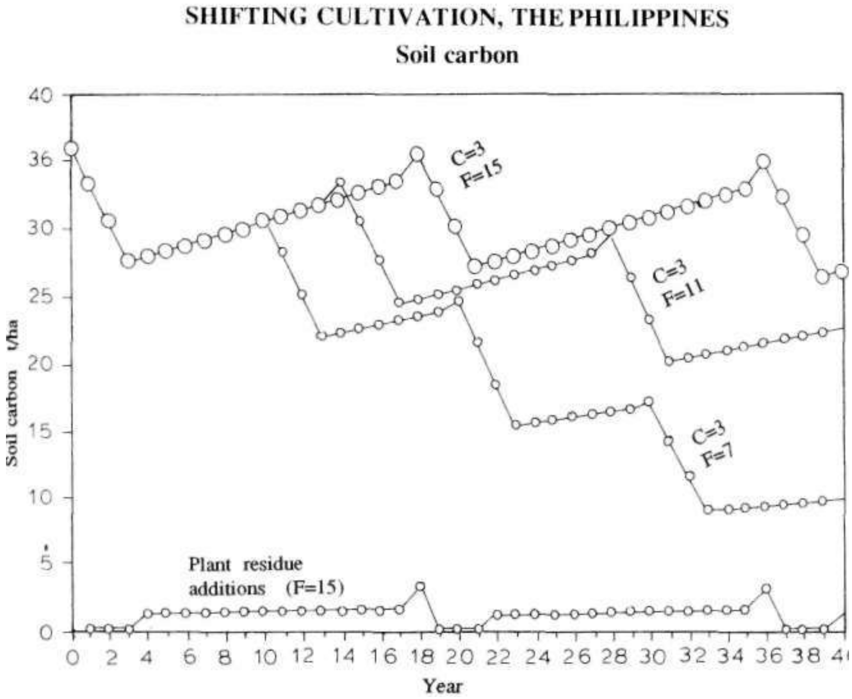


Figure 19. SCUAF outputs: changes in soil carbon under a rotational system, shifting cultivation, the Philippines. C = cultivation period in years, F = fallow period in years (data from Kellman, 1969).

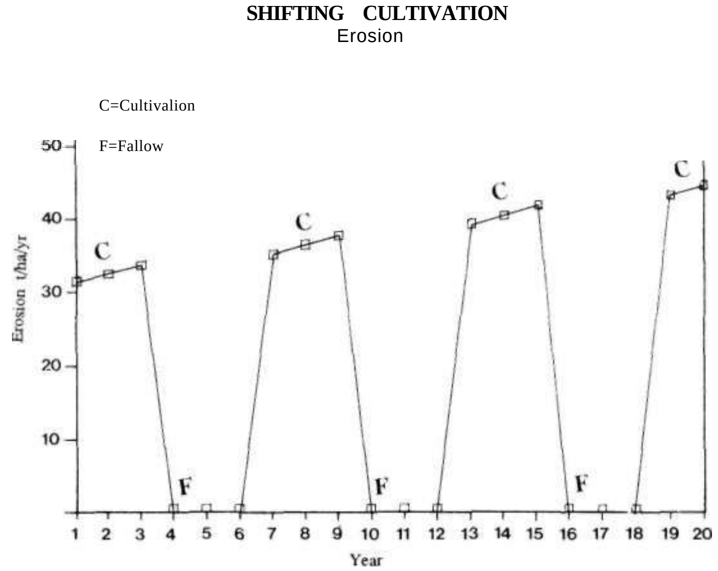


Figure 20. SCUAF outputs: changes in soil erosion under shifting cultivation with reduced fallow. Simulated data.

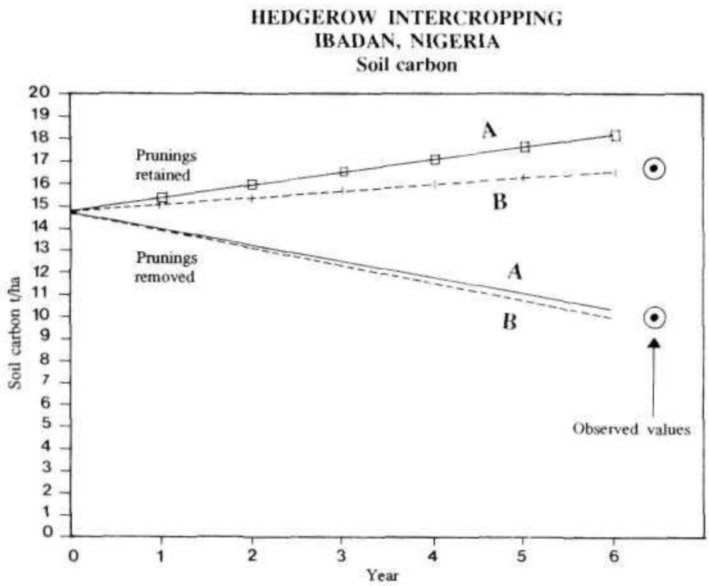


Figure 21. SCUAF outputs: changes in soil carbon under a spatial-zoned system. hedgerow intercropping, Ibadan, Nigeria. Lines marked A show predictions based on default values in the model, those marked B show modelling adjusted for experimental data (data from Kang et al., 1981, 1985).

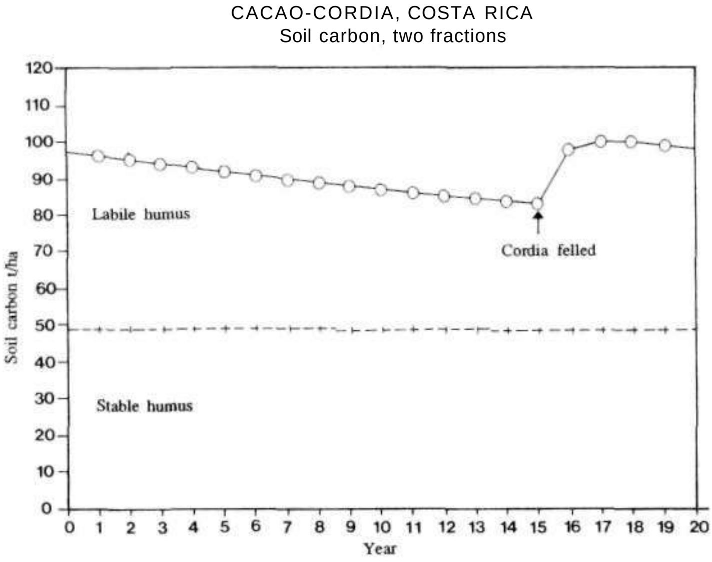


Figure 22. SCUAF outputs: changes in soil carbon and nitrogen under a spatial-mixed system, plantation crop combination of cacao with *Cordia alliodora,* Costa Rica (data from Alpizar et al., 1986. 1988). Carbon is modelled to 45 cm depth, assuming 50% is in stable form.

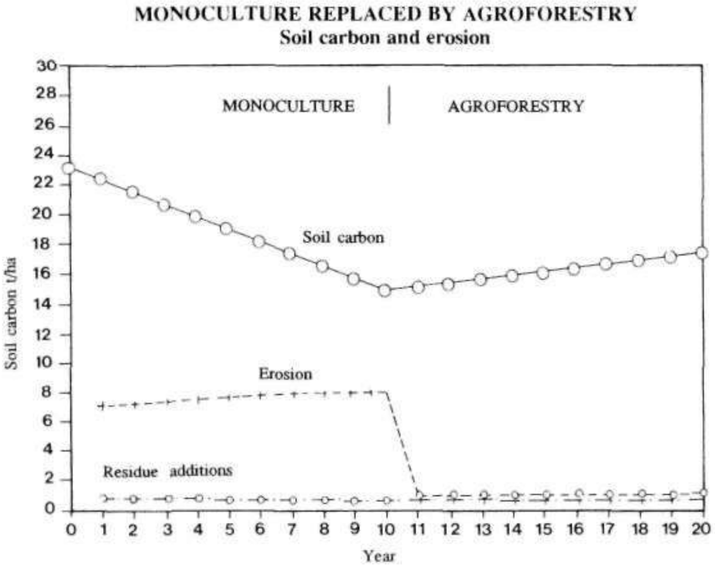


Figure 23. SCUAF outputs: changes in soil carbon and erosion, maize monoculture replaced bv agroforestry (assumptions and data for monoculture from Lelong et al.. 1984).

Chapter 16
Research

The need for research

Three conclusions from this review, taken in conjunction, indicate the need for research into the potential of agroforestry for soil conservation, treated in its broader sense as maintenance or improvement of soil fertility.

First, there exists in the tropics a widespread and increasing need for soil conservation. It is rare to find a study of existing agricultural systems which does not identify soil degradation, or fertility decline, as among the problems present, frequently one of the most serious. Where the land is sloping, erosion is one of the processes leading to decline in fertility; on steep slopes it is likely to be the dominant cause. Still more widely, the pressure of population upon land, combined with shortage of fertilizers and other inputs, has led to the situation formerly described as over-cropping and latterly as a failure to achieve sustainability. This is the situation in which, to meet the needs of the population, more is taken out of the soil than is put back into it, so causing degradation of a basic resource on which production depends.

Secondly, it has been shown that agroforestry appears to have the potential to control erosion, maintain soil fertility, and so lead towards sustainable land use. This applies not just to one system but to a range of agroforestry practices, each of which can be adapted into many different systems. Some at least of these practices are known to be acceptable to farmers, in that they are found as indigenous systems, whilst others have achieved a measure of acceptance in currently active extension projects. This range of design options means that there is scope to identify agroforestry systems suited to a wide range of environmental conditions and farmers' circumstances that are likely to contribute to soil fertility maintenance and sustainable land use.

Thirdly, it has been emphasized that much of the evidence for the previous conclusion is indirect. The capacity to control soil erosion is suggested by analysis of the causative factors and processes of erosion in relation to the characteristics of agroforestry systems. The potential to maintain soil fertility is inferred partly from the known beneficial effects of trees on soils. In the case of fertility maintenance, there are strong indications from indigenous agroforestry systems. But scientific evidence, in the narrow sense of controlled and replicated trials, is very scanty. At the time of writing, there is substantial experimental evidence only for hedgerow intercropping and dense, mixed plantation crop combinations, in both cases only from a few sites and under a narrow range of environments.

The conjunction of a large and growing need for soil conservation, a high apparent potential of agroforestry, and a scarcity of experimental evidence points clearly and strongly to the need for research.

THE NEED FOR RESEARCH

There is:

- a large and growing problem of soil degradation
- a high apparent potential of agroforestry to assist in the control of this
- a scarcity of experimental data to confirm this potential.

It is hard to imagine a combination of circumstances that so clearly indicates the need for research!

Levels of agroforestry research

At present, there is an explosion of activity in agroforestry research, the result of the rapid growth in awareness of its potential. Because of the urgency of the problems, brought about fundamentally by population growth and pressure upon natural resources, agroforestry is trying to achieve much in a short time. This calls for the structured planning of research.

Agroforestry systems are highly complex, involving the interactions of at least two plant components with each other and with climate and soil. As a consequence, scientific research in agroforestry can be thought of as falling into three levels: *what, why* and *how* (Huxley et at., 1989; Pinney and Young, in press) (Figure 24).

WHA T research is directed at questions of 'what happens?" It is intended to answer the immediate needs of farmers and other land users. Rural extension agents and farmers need advice on what tree species are appropriate to plant, in what number and arrangement, and with what management practices. Locally conducted trials of prototype systems, on-farm as well ason-station, are the level of research which directly precedes such advice.

WHY research seeks answers to questions of why the components of agroforestry systems perform in a certain way. Why does the crop on the upper side of a contour-planted hedge grow better than that on the lower side? Why is one tree species more competitive with an adjacent maize

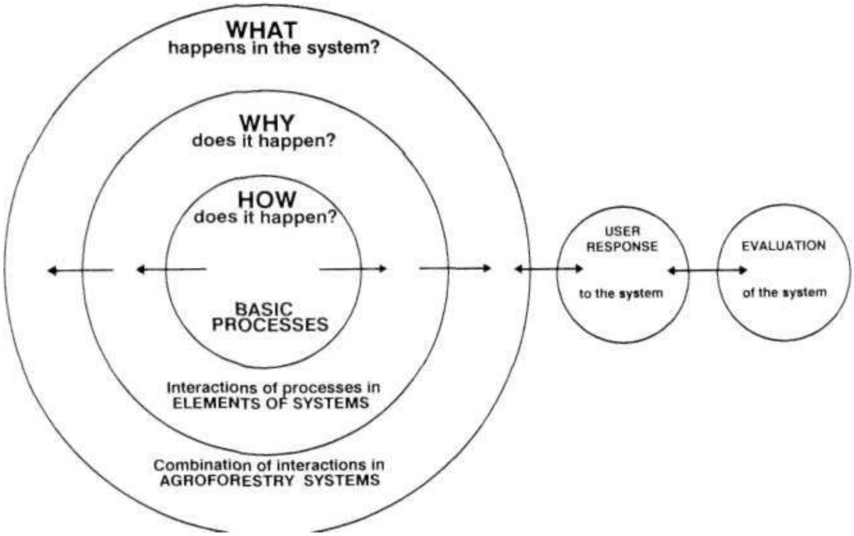


Figure 24. Levels of research in agroforestry (based on Pinneyand Young, in press).

crop than another? This level of work is trying to determine cause-and-effect relationships operating on a specific site (soil, slope) and under each year's weather conditions. *Why* research is needed in order to design the prototype tested in *what* research.

HOW research is concerned with the fundamental processes operating within systems. How are mineralization rates affected by moisture? How does assimilate pass between roots of trees and crops? At this level we are looking at specific processes and effects, which operate as associations of effects in 'why' research. Some research at this level is not specific to agroforestry, but involves basic processes of, e.g., microclimatology. soil physics, soil biology and plant nutrition.

Beyond these levels of purely scientific research there are two more stages—user response and evaluation. User response tests the reaction to proposed agroforestry systems of farmers or other land users. Formerly thought of as a one-way procedure, designing systems on scientific grounds and then testing their acceptability, it is now common to include on-farm research and farmers' opinions and suggestions at an early stage of research planning. A structure for doing this is one feature of the diagnosis-and-design procedure.

Evaluation seeks to test the overall desirability of proposed systems, on environmental, economic and social grounds. It can be carried out at two stages, *ex ante,* analysing the apparent benefits and drawbacks of a system prior to its testing, using assumed data on performance; and *ex post,* analysis after the system has been in operation for some years with a view to improving it for the future.

The present expansion of interest in agroforestry has come at a time when there is also a focus on 'useful' research, directed at meeting the practical 'needs of farmers'. As a result, current agroforestry research is heavily concentrated on trials of potential systems (*what* research), at the expense of studies of basic processes. The statement, 'Research should be directed towards the practical needs of farmers' is true; but the reasoning, 'Therefore it should consist of field trials of practical management systems' is false.

The drawback with *what* or 'try-it-and-see' research can be seen from an example. Consider a single practice, that of hedgerow intercropping. On a given site it would certainly be possible to test four hedge species, three within-row plant spacings, four between-row spacings and three pruning heights; with three replicates this would give 432 plots—without considering alternative agricultural crops! Some saving is possible through partial replication and confounding, or the use of systematic designs, but the research effort needed remains considerable. Then, having found the optimum combination, all that is known is that it works on that soil, and in the weather conditions for the years of the trial. To carry out field trials without an understanding of basic processes is like research into chemistry before knowledge of the periodic table.

Studies at the *why* level, into the functioning of processes and their interaction within elements of systems, can lead to greater efficiency of research effort. If we understand how trees and crops share, and compete for, climatic and soil resources, we should be able to design agroforestry prototypes, systems that are likely to operate satisfactorily in a given set of conditions. It would be far-fetched to suppose that our knowledge of environmental interactions in agroforestry will ever reach the point when a precisely functioning system can be designed in this way, but the principle is applicable. Trials (*what* research) can then be conducted over small margins of variation. In this way, research at the *how* and *why* levels can lead to far greater efficiency in field trials of prototype systems.

Each level of research is appropriate for different types of institutions. *How* research calls for specialized knowledge and facilities, and is appropriate for universities, international institutes and specialized national or zonal organizations. *Why* research can be conducted at an international level, but should also form part of the work of the larger national agroforestry research organizations. Field trials of prototype systems are conducted at national level, preferably through a network of sites in different environments.

Objectives of research

Research into the soil-fertility aspects of agroforestry is a subject of much complexity and has many practical problems. It can be conceived in two parts: specialized soil studies, and soil observations in general agroforestry research. It is important that soil studies should not be confined to specialized institutions. Given the importance of maintenance of fertility as a fundamental feature of most agrof'orestry systems, some basic soil observations should form part of all general-purpose agroforcstry field trials.

Specialized soil research

In specialized research, soil fertility is the primary objective. It is carried out by soil scientists at institutions possessing the necessary facilities. Some studies can be based on relatively straightforward methods of measurement, such as sampling and analysis, and require only good design and careful execution. Other aspects involve specialized techniques, for example isotope labelling (Young, in press, b).

The following problems require attention. In most cases, there is a need both for improvements in basic knowledge of the processes concerned, and for studies of their operation under trees and within agrof'orestry designs. 'Trees' refers both to individual trees and shrubs and to the tree component in agroforcstry systems:

- Soil erosion: functioning of factors and processes under tree-crop mixtures; barrier and cover functions; processes within partly permeable hedgerow barriers
- Soil organic matter: formation, decomposition, cycling effects on fertility; role of herbaceous, woody and root residues in formation
- Nutrient cycling, especially efficiency of nutrient uptake and recycling by trees
- Tree biomass production, litter quality and decomposition
- Root and mycorrhizal systems of trees, and their effects
- Effects of trees on soil physical properties
- Nitrogen fixation by trees
- Effects of specific tree species on soil properties; what constitutes a good tree for soil fertility
- Studies of soil fertility under agroforestry systems, including organic matter, nutrient cycling, erosion and monitoring of soil change.

The major questions for soil-agroforestry research, expressed in the form of 10 specific hypotheses, are given in the box on p. 218. For only one subject, namely nitrogen fixation by trees, is the current research effort on a scale adequate to the needs. An appraisal of the current evidence for and against each hypothesis is given in Young (1989a).

TEN HYPOTHESES FOR SOIL-AGROFORESTRY RESEARCH

1. Agroforestry systems can control erosion, thereby reducing losses of soil organic matter and nutrients.
2. Agroforestry systems can maintain soil organic matter at levels satisfactory for soil fertility.
3. Agroforestry systems maintain more favourable soil physical properties than agriculture, through a combination of organic-matter maintenance and the effects of tree roots.
4. Nitrogen-fixing trees and shrubs can substantially augment nitrogen inputs in agroforestry systems.
5. The tree component in agroforestry systems can increase nutrient inputs from the atmosphere and the B/C soil horizons.
6. Agroforestry systems can lead to more closed nutrient cycling, and so to more efficient use of nutrients.
7. Agroforestry systems offer opportunities to synchronize release of nutrients from decay of plant residues with requirements for uptake by crops.
8. The cycling of bases in tree litter can assist in reducing soil acidity, or checking acidification.
9. Agroforestry can be incorporated in systems for the reclamation of degraded soils.
10. In the maintenance of soil fertility under agroforestry systems, the role of roots is at least as important as that of above-ground biomass.

Soil observations in general agroforestry research

A component of soils research should form part of most agroforestry field trials, other than those directed at special aspects. It is fundamental to establish whether any proposed design, which is satisfactory in other respects, maintains the soil in a stable and productive condition; also it is desirable to gain some idea of the cycling of organic matter and nutrients.

The quantity and degree of sophistication of the measurements taken will vary according to facilities available and the nature of the agroforestry system under study. The following are suggested as a basic minimum of observations:

1. Before setting out a trial, take soil samples from the site, on a statistically based pattern, including from control plots, and have analyses carried

out. After three years, resample on a stratified design, based on components of the system, e.g., beneath and outside trees in mixed systems, or within hedgerows and crop alleys in hedgerow-intercropping systems. Repeat every three years, or when the trial is concluded. To reduce costs, only a proportion of the samples taken need be analysed in the first instance, the rest being done if the initial data indicate a likelihood of significant results.

2. Measure biomass production from all elements of the system, tree and crop, and its partitioning between leaf, fruit and wood. If possible, carry out analyses of the nutrient content of tree leaves and, preferably, other plant parts.
3. Make some attempt, however basic, to estimate root production and distribution. The simplest method is to cut a trench across selected tree-crop interfaces in the system and plot root distribution and mass.
4. If the trial is on sloping land, make some attempt to measure the rate of erosion. For samples taken from the eroded sediment, analyse organic matter and nutrient content.

Inclusion of such a set of basic soil observations in most trials could go far to provide, in five to seven years' time, the data needed to confirm on the basis of scientific evidence the potential of agroforestry for maintenance of soil fertility.

21. Research: a prototype demonstration plot in which hedgerow intercropping, using *Gliricidia sepium,* is coupled with grass strips and fruit trees. Maha Illuppallama, Sri Lanka.

22. Research: a tree/crop interface study, using *Leucaena leucocephala* with sorghum. Hyderabad, India.

23. Research: separating root interaction from above-ground effects by means of a buried polythene sheet. Hyderabad, India.

24. Research: a lysimeter for measuring leaching, with a tree growing on its soil. Dehra Dun, India.

Design of research

It would go beyond the scope of this review to discuss the design, techniques and problems of research in detail. It is hoped to make soil research in agroforestry the subject of a future ICRAF publication. A basis for rationalizing field studies is the distinction between rotational, spatial-mixed and spatial-zoned practices (Huxley, 1986a, 1986b) (p. 13). All that will be attempted here is to indicate the scope for design, and the relations between different levels of research, by means of two examples.

Erosion control under hedgerow intercropping

The apparent potential of hedgerow intercropping, or systems of contour-aligned hedges, to control soil erosion by water has been indicated above. The need is for a system that will reduce loss of nutrients and organic matter in eroded soil to acceptable levels. Control is achieved through a combination of the barrier effect of hedgerows and the cover effect of hedge prunings combined with crop residues. Design and management options exist in choice of hedgerow species, single or multiple hedgerows, within-row plant spacing, between-row spacing, and placement of prunings. Some of these options may be limited by acceptability to farmers, e.g. a requirement that prunings should be fed to livestock. There are very few existing experimental data. These needs and choices, within the framework of local conditions of climate, slope and soil, form the basis for the design of research (see Stocking, 1985a).

In this instance, it may be useful to include some system trials from the start, in view of the strong inferential evidence that success is likely. The first step is to design a prototype ('best bet') system, the second to test variations in selected variables. The design of the prototype could take into account considerations such as a hedgerow species with high survival and vigorous growth (as determined by basic multipurpose tree selection and evaluation, *not* as part of the erosion trials) and with moderate to slow leaf litter decay, to maintain soil cover during the period of erosive rains. Between-row spacing might in the first instance be made similar to that recommended for conventional conservation structures, for the climate, soil and slope angle. A prototype design based on these considerations could be set up on a plot of about 50 x 10 m (see below), possibly on two or more slope angles, and monitored for runoff volume, soil loss, and losses of organic matter and nutrients.

The time and cost required for multiple trials of complete systems is, however, considerable. Economy of effort can be made by including some *why-level* research, in this case studies of a single barrier hedge.

A possible design is shown in Figure 25. The assumption is that a suitable hedgerow species has been identified; the objective is to study the effects of barrier width, management of prunings and inter-row spacing, with the

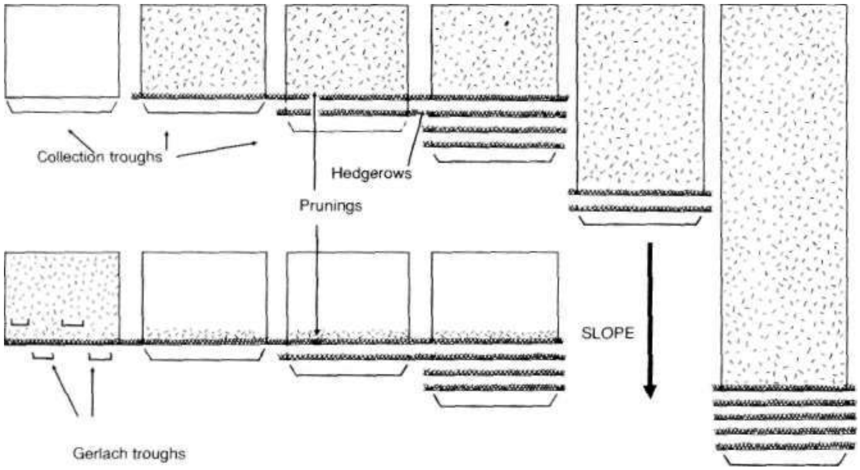


Figure 25. Treatments for studying the effects of a single hedgerow on runoff and erosion. Variables arc the number of lines of hedge in a hedgerow, whether prunings are distributed across the cultivated land or laid against the hedgerow, and the width of the cultivated area. Randomization and replication are not shown.

aim of being able to design a system which combines erosion control with minimum planting effort or loss of land. The design consists of single, double and four-row hedgerows, each with two pruning treatments, laid across the alley or piled against the barrier, all with some standard width of cropped land upslopc. Further plots test the double and four-row hedgerows with twice and four times the width of cropped land, plus a crop-only control. This gives nine plots in all, to be replicated as resources permit. If each plot is 5 x 5 m, plus 5 x 3 m for taking readings, one set of nine plots covers less land than a single system trial such as that outlined above. The results would permit design of a prototype system with considerably more confidence than is possible al present.

Most research stations would go no deeper than the above. However. some major sites should include some /unv-level research, in this case instrumenting a single hedgerow in such a way as to monitor subsurface as well as surface water flow, and actual sediment movement by means of tracer labelling, e.g. fluorescent or isotopic.

So/7 organic matter maintenance by trees

The capacity of trees, shrubs or hedgerows to replace losses of soil organic matter is fundamental to maintenance of fertility under all types of agroforestry practice—rotational, spatial-mixed or spatial-zoned. The achievement of this capacity is therefore a fundamental element in design.

At the *what* level, monitoring of organic matter would be included as part of the standard package of observations in system trials. Details would vary according to whether rotational, spatial-mixed or spatial-zoned systems were being tested. Purely from the viewpoint of soil fertility, a large number of trees is desirable (e.g. closely spaced hedgerows or shade trees), and a compromise must be found with the smaller number required by considerations such as shading and crop area.

In order to be able to design practical systems other than by guesswork, however, it is necessary to find out the amounts and types of plant residues that are needed to maintain specified levels of soil organic matter under local conditions of climate and soil type. The basis for such research is to add combinations of different types and amounts of plant biomass and monitor the resulting soil changes. Since crop fruit will invariably be harvested, the relevant types of plant material are tree leaf (possibly plus fruit), wood and roots, and crop leaf (residues) and roots.

Unlike system trials, in which the totality of interactions is investigated, in *why-level* soils research it is desirable to eliminate or minimize microclimatic effects. This can be done by making all plots as nearly uniform as possible in this respect, or by regular and low pruning.

Some possible treatments are shown in Figure 26. Each plot is of a size sufficient to obtain reasonably uniform plant growth and permit repeated soil sampling, perhaps 5 X 5 m as a minimum; it should be surrounded by guard rows of the same plants and treatments. There are control plots of trees only (receiving tree leaf, wood and root residues), crops only (receiving crop leaf and root residues), and an area tilled but with neither trees nor crops. This last is called a 'kill SOIVT plot, the aim being to follow the rate of loss of soil organic matter (SOM) without renewal from any source.

For other treatments, tree and crop above-ground residues can be included or excluded by manual transfer of prunings and litter. Root residues from adjacent plants can be excluded by buried plastic sheets parallel to hedgerows or, less easily, surrounding individual trees. It may be useful to include amounts of plant material greater than that likely to be obtainable in practical systems, the better to establish the functioning of processes.

The lower block in Figure 26 is for comparison with a rotational system. The proportion of trees to crops is the same as in some of the spatial plots, perhaps 25% of the total area. The block of trees is rotated around the area at two- or three-year intervals, cropping the remaining part. Such a comparison between spatial systems and rotational systems, with the same proportions of tree and crop but substituting interactions over time to those in space, is a valuable feature in many kinds of agroforestry research besides studies of soil fertility. Plots are sampled annually to monitor changes in soil organic matter, together with soil physical and chemical conditions and crop yield.

The *how* level of research in this case might be based on carbon-14 isotope labelling, following the fate of different kinds of plant residue added to the soil.

The same approach, the combination of system trials with studies of the critical elements of the system, can be applied to nutrient cycling and other aspects of soil fertility.

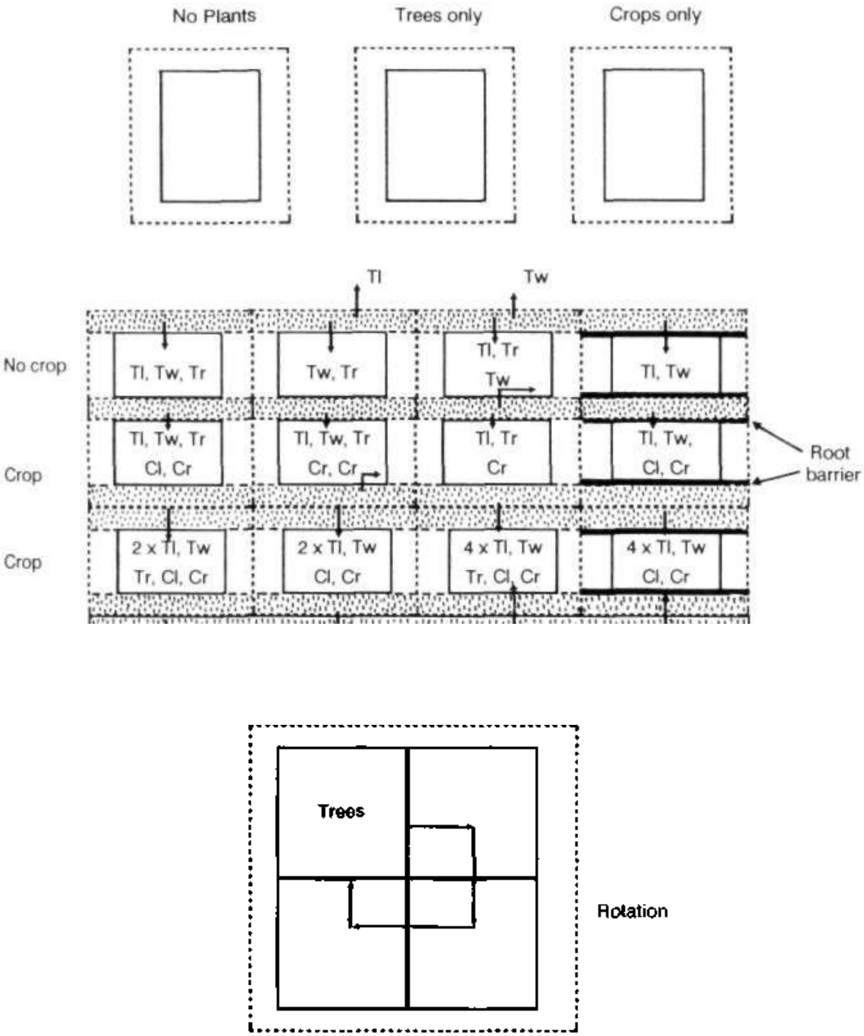


Figure 26. Treatments for studying the effects of tree and crop residues on soil organic matter. Letters indicate which plant residues are applied to the soil, as follows: T = tree, C = crop, 1 = leaf, w = wood, r = root, 2 x = at twice the standard rate, 4 x = at four times the standard rate. Randomization and replication are not shown.

Techniques and observations

Many of the observations and assumptions made in agroforestry are similar to those in agricultural research. Others require adaptation to the special circumstances of tree and crop components.

For soil-erosion research, the former standard US plot, 20 x 2 m (0.01 acres), is no longer universal in agricultural studies and presents problems in agroforestry. It is too small to obtain sufficiently homogeneous, or representative, coverage in mixed tree-crop systems. A few plots of this size may be included to permit comparison with the large body of existing data based upon it. Larger plot sizes are currently in use for most agroforestry system trials, for example at Dehra Dun, India (90 x 15 m), Ibadan, Nigeria (70 x 10 m), Machakos, Kenya (40 x 40 m) and Maha Illuppallama, Sri Lanka (100 X 40 m).

The plot approach to erosion measurement is complemented by first-order catchment studies recording runoff and sediment content at an outlet flume. It is of the utmost importance that measurements should include analysis of the organic matter and nutrient content of eroded material, in addition to the mass of soil lost.

For research into soil fertility, many observations are the same as in agricultural trials. A useful basic set of methods of analysis is given in the methods handbook of the Tropical Soil Biology and Fertility programme (Anderson and Ingram, 1989). Five aspects may be emphasized:

1. It is fundamental to measure all rates of biomass production, by tree and crop components, partitioned into leaf, fruit, wood and roots; to record all additions and removals of organic matter to and from the plot or system under study; and where possible, to analyse samples of these plant parts for their nutrient content.
2. As a special case of the above, some attempt should be made to measure standing biomass and production of root systems, in view of their importance to the organic-matter and, probably, nutrient economies. Methods are given in Anderson and Ingram (1989).
3. Monitoring should cover both soil properties and plant growth. To measure soil changes alone is insufficient: the properties determined in soil analysis are individual variables, in some cases artificial, and may not fully indicate soil fertility. Conversely, if plant growth (or even crop yield) is taken as the sole criteria for evaluation, then the research falls entirely into the 'what happens" level. The soil is then treated as a "black box", and one has no evidence about causes of the observed effects.
4. Micro variability of properties in space is a severe problem in all kinds of soil research. It is not only that substantial soil changes can occur over distances of a few metres. Additional to such variation, samples of a soil which appears completely uniform show coefficients of variation in analytical values of the order of 25% for carbon and nitrogen and 30

to 70% for other nutrients (Dent and Young, 1981, pp. 92-95). To identify significant changes requires substantial numbers of samples (Cochrane and Cox, 1957, pp. 20—21). Use of composite sampling can reduce the costs of analysis.

5. Most agroforestry research is environment specific Young, 1986b. It cannot be assumed that a practice or system which is effective in one combination of climate, landforms, soil and vegetation will be equally effective in another. Thus each practice needs to be tested for the major climatic zones, the main soil types present and, where relevant (sylvopastoral systems), for vegetation types.

Chapter 17
Conclusion

Previous reviews

In the major previous review of soil productivity under agroforestry, Nair (1984 pp. 68-69, 72) concluded that:

> The inclusion of compatible and desirable species of woody perennials on farmlands can result in a marked improvement in soil fertility.... Agroforestry is only one potential approach to land use, which, if adopted properly, may prove superior to some other use approaches in some situations.... Properly practised, the system is likely to use the nutrients more efficiently and cost effectively, and to increase the sustainability of production from the land.... [However,] the concepts have to be validated by field research before site-specific soil management practices can be recommended.

Reviewing the effects of tropical agroforestry systems on soil erosion by water, Wiersum (1984, pp. 231,237) found that:

> Individual trees cannot be expected to exert the same protective effect as undisturbed forest ecosystems. The key to controlling erosion in agroforestry does not lie in the presence of trees themselves, but rather in good management practices.... Such management practices do not only include methods of maintaining a direct soil cover, but may also entail structural measures such as terracing.

In a recent account of soil productivity and sustainability under agroforestry systems, Sanchez (1987, pp. 206, 219) gave as the basic soil-agroforestry hypothesis:

> Appropriate agroforestry systems improve soil physical properties, maintain soil organic matter, and promote nutrient cycling.... While evidence exists for the beneficial effects on soils of certain agroforestry technologies (especially on more fertile soils), there is a tendency for over-generalization and extrapolation of soil productivity and sustainability benefits to other

more marginal sites. The time has come to bring science into the picture and systematically test the effects of agroforestry systems on different soils, and vice versa.

Each of these conclusions combines, in different ways, acceptance of a potential with words of caution. For Nair, writing before the existence of appreciable agroforestry research, it is that the concepts have to be validated before they can be recommended in the field. Wiersum warns that agroforestry does not automatically control erosion, but only with good design and management. Sanchez's proviso is that optimistic findings of a few experimental studies to date should not be uncritically extended to all soil types and agroforestry practices.

The present review

The conclusion from the present study is similar to those of the above reviews, but differs in emphasis. By including the control of erosion, the general soil-agroforestry hypothesis can be stated as follows:

Appropriate agroforestry systems have the potential to control erosion, maintain soil organic matter and physical properties, and promote efficient nutrient cycling.

Appropriate means suited to the physical environment and to social and economic conditions, properly designed and well managed. The achievement of such designs requires a proper foundation of research.

The evidence available is of two kinds, direct and indirect. Direct evidence, based on studies of the effects of agroforestry systems upon soils, is at present sparse, but almost invariably supports the basic hypothesis. In addition, there is much indirect evidence, drawn from agriculture, forestry and soil science, of the beneficial effects of trees on soil fertility and the potential to make use of this capacity in agroforestry systems.

Taking these two kinds of evidence together, it is concluded that the general soil-agroforestry hypothesis is essentially true. There is a con-

THE GENERAL SOIL-ACROFORESTRY HYPOTHESES

Appropriate agroforestry systems have the potential to:

- control erosion
- maintain soil organic matter and physical properties
- promote efficient nutrient cycling.

It is concluded that this hypothesis is essentially true, and applicable to a wide range of environmental conditions.

siderable potential for soil conservation through agroforestry, both in control of erosion and by other means of maintaining soil fertility. This potential applies to the majority of agroforestry practices, and over a wide range of climatic zones and soil types. Those agroforestry practices with a specific potential for soil conservation are given in Table 33.

Table 33. *Agroforestry practices with potential for soil conservation.*

Agroforestry practice	Control of erosion	Maintenance or improvement
Improved tree fallow		+
Trees on cropland		+
Plantation crop combinations	+ +	+ +
Multistorey tree gardens	+ +	++
Hedgerow intercropping	+ +	+ +
Trees on erosion-control structures	+ +	
Windbreaks and shelter-belts	+ +	+
Trees on pastures	(+)	+ +
Reclamation forestry leading to multiple use	+ +	+ +

25. Farming landscape with trees. Embu. Kenya.

One major qualification to this conclusion, arising from the scope of the present study, is that it does not take into account availability of soil water. This is frequently a limiting factor for plant growth in dry subhumid and semi-arid environments, and a large research effort is needed into soil-water processes under agroforestry. This will need to combine evidence drawn from research in soil physics, agriculture and forestry with experimental studies of soil-water interactions at the tree-crop interface and under agroforestry systems. A starting point is set by a recent symposium on applications of meteorology to agroforestry (Darnhofer and Reifsnyder, 1989).

A second qualification is that already noted, the paucity of experimental evidence. To confirm the apparent potential, and to permit the design of agroforestry systems suited to specific environments, a major research effort is called for.

If research succeeds in confirming the hypotheses and conclusions reached from the limited evidence currently available, then agroforestry has the potential to make a major contribution to soil conservation and sustainable land use.

SUMMARY

The following is a summary of the conclusions reached in this review. Summaries also have been given in Young (1987b, and in press, a). 'Trees' refers to all woody perennials, including trees, shrubs and bamboos. 'Crops' includes both agricultural crops and pastures.

Part I. Soil Conservation and Agroforestry

Soil conservation and sustainability

Sustainability refers to productivity combined with conservation of the natural resources on which production depends. Maintenance of soil fertility forms a major component of sustainable land use.

The primary objective of *soil conservation* is maintenance of soil fertility. To achieve this, control of erosion is one necessary, but by no means sufficient, condition. Equally important are maintenance of the physical, chemical and biological soil conditions that are favourable for plant growth.

Agroforestry

Agroforestry refers to land-use systems in which trees or shrubs are grown in association with crops (agricultural crops or pastures), in a spatial arrangement or a rotation, and in which there are both ecological and economic interactions between the trees and other components of the system.

An *agroforestry practice* is a distinctive arrangement of components (e.g. trees, crops, pastures, livestock) in space and time. An *agroforestry system* is a specific local example of a practice. There are thousands of agroforestry systems, traditional and modern, but only some 20 distinct practices. Thus, agroforestry offers a wide range of choice, giving opportunities to design systems suited to a variety of physical environments and social and economic conditions.

Agroforestry practices and systems can be classified according to their components and their temporal and spatial arrangement. The division into *rotational, spatial-mixed* and *spatial-zoned practices* is related to the types and degrees of interaction between tree and crop components, and forms a basis for research (see Table 4, p. 12).

Management options for restoring or maintaining soil fertility may be constrained by:

- type of land: the option is only applicable on land of certain kinds
- extent of land: the option requires land additional to that under cultivation
- supply problems: availability or cost of inputs.

Most non-agroforestry methods suffer from one or more of these constraints. The various agroforestry practices are applicable to a wide range of environmental conditions and do not require inputs that are in short supply or costly. The land requirements of the tree component may be compensated either by higher crop yields or by the value of products from the tree. Thus, agroforestry is widely applicable as a practical management option. One of its greatest potentials is to help solve land-use problems in areas of sloping land.

Part II. Agroforestry for Control of Soil Erosion

Trends in soil-conservation research and policy

The earlier approach to soil conservation centred upon rates of soil loss. The requirements of arable cropping were taken as fixed, and hence conservation measures were directed at reducing runoff, through earth structures. On the basis of assessed land capability, much sloping land was regarded as only suitable for non-arable use. In extension, soil conservation was often treated in isolation, and sometimes on the basis of quasi-legal compulsion.

Arising from problems in the earlier approach and from recent research, greater attention is now given to the effects of erosion on soil properties, fertility and crop yields. In conservation, there is greater emphasis on maintaining a soil cover, as compared with checking runoff. Where sloping land is already under arable use, means must be found of making this sustainable. In extension, it is recognized that conservation is only likely to succeed where it is implemented through the willing cooperation of farmers. It must therefore be in their perceived interests, as an integral part of improvements leading to higher production.

Aspects of these recent trends significant to agroforestry are:

- The potential of agroforestry for erosion control should be considered jointly with that for maintenance of fertility.
- Particular attention should be given to the capacity of tree litter to maintain soil cover.
- It is important to develop agroforestry systems with the potential for sustainable land use on sloping lands.
- Through its capacity to combine production with conservation, agroforestry offers a means of securing the cooperation of farmers.

Soil erosion is the cause of substantial lowering of crop yields and loss of production. The effect on yields is in general greater on tropical than on temperate soils, and greatest on highly weathered tropical soils. The major causes of such yield reduction are loss of organic matter and nutrients and, in dry areas, loss of runoff and lowering of available water capacity. Hence, agroforestry practices which combine maintenance of fertility with control of soil loss are of particular importance.

Where erosion is treated as simple loss of soil depth, it is frequently difficult to justify conservation in economic terms. Economic justification is frequently possible, however, on the basis of prevention of crop-yield losses. Agroforestry methods usually have lower initial costs than terracing or bunds, and also have the potential for maintaining or increasing crop yields. It is therefore likely, other things being equal, that conservation by means of agroforestry will show more favourable results from economic analysis than conservation by means of earth structures.

Soil conservation by means of an enforced policy frequently does not work. Conservation is likely to be most effective where it is conducted with the active cooperation of farmers, in their perceived interests, and integrated with other measures for agricultural improvement. This situation is in good accord with the diagnosis and design approach to the planning of agroforestry.

The barrier and cover approaches to erosion control

Erosion can be controlled through checking downslope flow of water and entrained soil by means of barriers to runoff, the *barrier approach*, and through maintenance of a ground surface cover of living plants and litter, the *cover approach*. The effect of soil cover is both to check raindrop impact and to provide dispersed micro-barriers to runoff.

Models for the prediction of erosion arc based on the controlling variables of rainfall erosivity, soil credibility, slope (angle and length) and soil cover. A review of these models shows that there arc equal or greater opportunities to reduce erosion by means of the cover approach than by the barrier approach.

Experimental evidence

Experimental evidence supports that of models in showing the high potential for erosion control of soil cover. The effect of tree canopy cover is relatively small, and may even be negative. Ground litter or mulch, on the other hand, is highly effective; a litter cover of 60% will frequently reduce erosion to low levels, even without additional measures of the barrier type. The potential of agroforestry for erosion control therefore lies in its capacity to maintain a ground surface cover of greatest litter during the period of erosive rainfall.

On the basis of the limited available evidence, the effects of agroforestry on the causative factors of erosion appear to be as follows:

- Rainfall erosivity is often reduced only slightly (by the order of 10%), and may sometimes be increased, by the presence of a tree canopy.
- The resistance of the soil to erosion, which commonly decreases under continuous arable use, can be sustained through the capacity of agroforestry to maintain soil organic matter.
- Reduction of runoff, and thereby of effective slope length can be achieved firstly by means of barrier hedgerows, and secondly by combining trees with earth structures.
- As noted above, there is a considerable potential to increase soil cover by means of plant litter.

Thus, in the design of agroforestry systems for erosion control, the primary aim should be to establish and maintain a ground surface cover of plant litter. This conclusion is supported by a range of convergent evidence, direct and inferential.

The presence of trees does not necessarily lead to low rates of erosion. What matters is the spatial arrangement of the trees and, especially, the way in which they are managed.

Data on recorded erosion rates under agroforestry are sparse, although more measurements are in progress. The limited existing data support the hypothesis that agroforestry systems have the potential to reduce erosion to acceptable rates.

Hedgerows differ from ditch-and-bank structures in that they are partly permeable barriers. Standard criteria for design of conservation works, based on impermeable earth barriers, are not necessarily transferable without modification to barrier hedges. An advantage arising from partial permeability is that hedgerow barriers are less likely to be destroyed during heavy storms. Research is needed into the effects of hedgerow barriers on runoff and soil movement.

Agroforestry practices for erosion control

The role of trees and shrubs in erosion control may be direct or supplementary. In *direct use*, the trees are themselves the means of checking runoff and soil loss. In *supplementary use*, control is achieved primarily by other means (grass strips, ditch-and-bank structures, terraces); the trees serve to stabilize the structures and to make productive use of the land which they occupy.

The functions of the tree component in erosion control may include any of the following:

- to reduce water erosion by a surface litter cover
- to act as a runoff barrier by closely planted hedgerows, coupled with the litter that accumulates against them
- to prevent decline in soil-erosion resistance, through maintenance of organic matter
- to strengthen and stabilize earth-conservation structures where present
- to reduce wind erosion by windbreaks and shelterbelts (not reviewed here)
- to make productive use of the land taken up by conservation structures
- to serve the function, partly psychological, of helping to link erosion-control practices with production, thereby making these an integral and permanent part of the farming system.

Methods of erosion control through agroforestry have been designed, recommended or are being tried in a number of countries, in some cases on the basis of experimental results, at other sites on an empirical or trial basis.

Firm knowledge of the effects of agroforestry practices on erosion is sparse. On the basis of such data as exist, the probable effects may be summarized as follows (see Table 10, p. 76).

Rotational Practices. Improved tree fallow can check erosion during the period of fallow, but erosion control as a whole will depend mainly on practices during the cropping period. For *taungya,* limited evidence suggests there may be some increase in erosion during the cropping period, as compared with pure tree plantations, but probably not a substantial adverse effect.

Spatial-mixed practices. Plantation crop combinations and *multistorey tree gardens,* including home gardens, can control erosion through the provision of a dense, regularly renewed, ground surface cover. In the case of multistorey gardens, such control is intrinsic to the nature of the practice. For plantation crop combinations, control depends on management, specifically the maintenance of a ground cover of litter.

Spatial-zoned practices. For *hedgerow intercropping* (alley cropping, barrier hedgerows) there is substantial inferential, and limited experimental, evidence of potential erosion control through provision of a litter cover on the cropped alleys and a barrier function through the hedgerows. Effective erosion control will not be automatic, and will vary with detailed design and management practices. Given the apparently high potential coupled with the sparsity of experimental data, there is an urgent need for controlled measurements of erosion rates under this practice.

The practice of *trees on erosion-control structures* involves the supplementary use of the tree component. Tree planting can make productive use of the land occupied, help to stabilize the structures and in some cases add to their protective effects. It also fulfils a psychological function, making it more likely that the structures will be perceived as beneficial and thus maintained. This applies to trees on ditch-and-bank structures, grass barrier strips, and terraces.

Although not covered in this review, the established potential of *windbreaks and shelterbelts* to control wind erosion may be noted for completeness.

Sylvopastoral practices. Erosion control on grazing land depends primarily on the basic, established practices of pasture management, notably limitation of livestock numbers and rotation of grazing. Sylvopastoral methods alone are unlikely to succeed, but can contribute when carried out in conjunction with other measures for pasture management. A specific potential is for reducing grazing pressure through provision of protein-rich fodder at those times of the year when grass pasture is scarce.

Reclamation forestry and watershed management. There are opportunities to integrate agroforestry with the known benefits of *reclamation forestry.* A period of reclamation is followed by controlled productive use, retaining part of the tree cover for continued conservation.

Agroforestry can form a component, together with other major kinds of land use, in *integrated watershed management.*

Part III. Agroforestry for Maintenance of Soil Fertility

Soil fertility and degradation

Soil fertility is the capacity of soil to support the growth of plants, on a sustained basis, under given conditions of climate and other relevant properties of land. It is part of the wider concept of land productivity.

Diagnosis of the problem of low crop yields should distinguish between low soil fertility, caused by natural soil conditions, and decline in soil fertility, brought about by past land use. These two causes may call for different kinds of action.

Effects of trees on soils

The association between trees and soil fertility is indicated by the high status of soils under natural forest, their relatively closed nutrient cycles, the soil-restoring power of forest fallow in shifting cultivation, and the success of reclamation forestry. More detailed evidence is provided by comparisons of soil properties beneath and outside tree canopies.

Trees maintain or improve soils by processes which:

- augment additions of organic matter and nutrients to the soil
- reduce losses from the soil, leading to more closed cycling of organic matter and nutrients
- improve soil physical conditions
- improve soil chemical conditions
- affect soil biological processes and conditions.

Some of these processes are proven, others are hypotheses in need of testing (see Table 14, p. 97; Figure 7, p. 98).

Soil organic matter

Soil organic matter plays a key role in maintaining fertility, particularly, but not only, under low-input conditions. Its main effects are to improve soil physical properties and to provide a reserve of nutrients, progressively released by mineralization.

Herbaceous plant residues applied to the soil initially decompose rapidly, with a half-life in tropical soils of less than six months. Woody residues decompose more slowly. During decomposition there is a loss of carbon and a release of nutrients. The remaining material becomes soil organic matter or humus. There are at least two fractions of humus, labile and stable. It is largely the labile fraction which contributes to nutrient release, and which is directly affected by management. It is not known whether woody residues confer distinctive properties on soil humus.

Taking as a basis the established cycling of organic matter under natural forest and decline under cultivation, it is feasible to construct a cycle under agroforestry which maintains equilibrium in soil organic matter. The following are approximate rates of above-ground biomass production which, if returned to the soil, can be expected to maintain organic matter at levels acceptable for soil fertility:

Humid tropics	8000kg DM/ha/yr
Subhumid tropics	4000 kg DM/ha/yr
Semi-arid zone	2000 kg DM/ha/yr.

The net primary production of natural vegetation communities is somewhat higher than these values, whilst that from trees used in agroforestry can approach, and occasionally exceed, that from natural vegetation (see Table 20, p. 22).

In agroforestry systems, the requirements to maintain soil organic matter can certainly be met if all tree biomass and crop residues are added to the soil. If the woody part of the tree is harvested, this becomes more difficult, and it is impossible if tree foliage and crop residues are also removed.

The rate of litter decay is influenced by its quality, or relative content of sugars, nutrient elements, lignin and other polyphenols. Rates of decay determine the timing of nutrient release. It is desirable to synchronize nutrient release with plant uptake requirements. Agroforestry systems offer opportunities to manipulate this release, through selection of tree species and timing of pruning.

Plant nutrients

Nitrogen-fixing trees and shrubs, growing within practical agroforestry systems, are capable of fixing about 50-100 kg N/ha/yr. The nitrogen returned in litter and prunings may be 100-300 kg N/ha/yr, partly derived by recycling of fertilizer nitrogen (see Table 22, p. 131).

The second major role of trees is to improve the efficiency of nutrient cycling. Mechanisms are uptake from lower soil horizons, reduction of leaching loss by tree-root systems, balanced nutrient supply, and improvement in the ratio between available and fixed minerals. For a tree-leaf biomass production of 4000 kg DM/ha/yr, the potential nutrient return in litter, as kg/ha/yr, is of the order of 80-120 for nitrogen, 8-12 for phosphorus, 40-120 for potassium and 20-60 for calcium. These amounts are substantial in relation to the nutrient requirements of crops (see Table 23, p. 136; Figure 12, p. 132; Figure 13, p. 134).

In research, the emphasis on nitrogen fixation has led to a comparative neglect of the effects of agroforestry systems on other nutrients, and on the potential to achieve more closed cycles of all nutrients under agroforestry as compared with agriculture.

Other soil properties and processes

There is substantial evidence that trees in agroforestry systems can help to maintain soil physical properties, a major element in soil fertility.

The base content of tree litter can help to check acidification. It is unlikely to be of sufficient magnitude appreciably to moderate the acidity of strongly acid soils, other than in systems which make use of tree biomass accumulated over many years.

As a means of forest clearance, manual and shear-blade methods leave the soil in better condition than bulldozer clearance. The efficiency of rotational systems is necessarily reduced if burning is practised, with consequent loss of most stored carbon, nitrogen and sulphur.

As shown in Part II of this review, agroforestry has a potential for control of soil erosion. Since the major adverse effect of erosion is loss of organic matter and nutrients, the potential to control erosion constitutes a major means of maintaining soil fertility.

The **role of roots**

There has recently been increasing recognition of the importance of roots as a component of primary production. Root biomass of trees is typically 20-30% of total plant biomass (or 25—43% of above-ground biomass). However, net primary production of roots is substantially more than standing biomass, owing to the turnover of fine roots. Roots form an appreciable store of nutrients, and since they are almost invariably returned to the soil, constitute a substantial element in nutrient recycling.

Tree root systems, together with their associated mycorrhizae, improve the efficiency of nutrient cycling, defined as the ratio between plant uptake and losses by leaching and erosion. They also contribute to soil physical properties.

The key to making use of root and mycorrhizal systems in agroforestry lies in maximizing these positive effects whilst reducing tree-crop competition for moisture and nutrients. There is a clear need for more knowledge of root growth and functioning in agroforestry systems.

Trees and shrubs for soil improvement

The properties which constitute a good soil-improving tree, and thus the means of recognizing one, are not well established. The following are contributory:

- high nitrogen fixation
- high biomass production
- a dense network of fine roots or associated mycorrhizae
- some deep roots
- high, balanced nutrient content in the foliage
- appreciable nutrient content in the roots
- either rapid litter decay, where nutrient release is desired, or a moderate rate of litter decay, for protection against erosion
- absence of toxic substances in foliage and root exudates
- for reclamation or restoration, a capacity to grow on poor soils.

Fifty-five tree and shrub species, belonging to 32 genera, are identified which have a potential to maintain or improve soil fertility (Table 27, p. 159). Species with particularly high potential include:

- *Acacia albida*
- *Acacia tortilis*
- *Calliandra calothyrsus*
- *Casuarina equisetifolia*
- *Erythrina poeppigiana*
- *Gliricidia sepium*
- *Inga jinicuil*

- *Leucaena leucocephala*
- *Prosopis cineraria*
- *Sesbania sesban.*

Agroforestry practices for soil fertility

Most reported indigenous agroforestry systems (other than shifting cultivation) have a spatial-mixed structure, in contrast to the spatial-zoned systems which are the focus of much current research. In the majority of indigenous systems, control of erosion, maintenance of fertility, or both, are an identified function. Use of poor soils and reclamation of degraded land are also found (see Table 28, p. 170).

A substantial body of research results on soil exists only for shifting cultivation and the plantation-crop combination of coffee or cacao with combinations of *Erythrina, Inga* and *Cordia.* Data on hedgerow-intercropping systems come mainly from one site, at Ibadan, Nigeria, although further studies are in progress or planned. Soils data on other agroforestry practices are sparse.

Results from soils research on agroforestry practices include the following.

Rotational practices. For *shifting cultivation,* dependent on natural forest fallow, there is no way of escaping the large land requirement implied by the fallow-to-cropping ratio necessary to restore soil fertility. Owing to population pressure upon land, this formerly stable system is no longer sustainable in many areas.

The potential of *improved tree fallows,* and more generally the relative effects on soils of rotational and spatial combinations of trees and crops, are not known.

Spatial-mixed practices. Plantation crop combinations of coffee or cacao with *Erythrina, Inga* and *Cordia* are characterized by a large return of organic matter and nutrients to the soil, in litter and prunnings, together with a moderate level of nitrogen fixation. Where fertilized, the nutrient return includes nutrients in fertilizer, demonstrating the efficiency of the system in promoting nutrient retrieval and recycling.

Multistorey tree gardens, including home gardens, through a high rate of biomass production and efficient nutrient recycling, exemplify conditions of sustainability, by combining high productivity with complete conservation of resources.

Spatial-zoned practices. In *hedgerow intercropping* (alley cropping), a large biomass production can be obtained from hedgerows, together with nitrogen fixation and substantial return of nutrients in prunnings. It may be possible to design systems in which crop yields, per unit of total area, are greater with hedgerows than in monocropping. The one available soil-monitoring study showed successful maintenance of fertility for six years. Roots are probably a contributory factor (see Table 32, p. 000).

The presence of a given agroforestry practice is by no means sufficient to ensure maintenance of soil fertility. Equally important are: (1) the design of the system in relation to local environmental and socio-economic conditions; (2) good management of the system; (3) the integration of agroforestry with the farming system as a whole.

Part IV. Agroforestry for Soil Conservation

Modelling soil changes under agroforestry

A computer model has been developed, Soil Changes Under Agroforestry (SCUAF), to predict the effects on soils of specified agroforestry systems within given environments. This is a relatively simple input-output model, covering prediction of changes in erosion, soil organic matter and nutrients. Illustrative outputs are given in Figures 19-23 (pp.209-211). The SCUAF model can be used as an aid to the design of agroforestry research.

The need for research

In less-developed countries of the tropics and subtropics, there is a large and growing problem of decline in soil fertility. This is caused both by erosion and by other processes of soil degradation. Indirect evidence, together with limited experimental data, indicate that many agroforestry practices have the potential both to control erosion and to check other forms of soil degradation. The combination of a high apparent potential with a scarcity of experimental results points clearly and strongly to the need for research.

Agroforestry research can be conducted at three levels: 'What happens?" or trials of systems, 'Why does it happen?' or studies of elements within systems or interactions between components, and 'How does it happen?" or studies of basic processes. Trials of systems alone *(what* research) arc inefficient as a means of advancing knowledge, owing to the large number of variables and the site-specific weather and soil conditions. Studies of elements within systems *(why* research) lead towards the efficient design of prototype systems, which can then be tested over a limited range of variation. A better knowledge of basic processes will help in understanding the functioning of components, their interactions and thereby systems.

Research into soil conservation by means of agroforestry can be considered in two parts: specialized studies and soil aspects of general agroforestry research. Subjects for specialized soil research are listed, together with a suggested minimum set of soil observations to be included in general agroforestry research. A set of ten hypotheses for investigation by specialized soil-agroforestry research is presented p. 218.

Examples of research designs at the *why* level are given, together with notes on experimental techniques and observations. Further studies of research methods specific to the problems of agroforestry are required.

Conclusion

The general soil-agroforestry hypothesis is that:

Appropriate agroforestry systems control erosion, maintain soil organic matter and physical properties, and promote efficient nutrient cycling.

It is concluded that this hypothesis is essentially true. There is a considerable potential for soil conservation through agroforestry, both in control of erosion and by other means of maintaining soil fertility. This potential applies to many agroforestry practices and over a wide range of climatic zones and soil types (see Table 33, p. 231).

If research succeeds in confirming this conclusion, then agroforestry has the potential to make a major contribution to soil conservation and sustainable land use.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACIAR: Australian Centre for International Agricultural Research (Canberra, Australia)
AGLS (FAO): Agriculture Department, Land and Water Development Division, Soil Resources, Management and Conservation Service (Rome, Italy)
ASA: American Society of Agronomy (Ankeny, Iowa, USA)
ASAE: American Society of Agricultural Engineers (St. Joseph, Michigan, USA)
BOSTID: Board of Science and Technology for International Development (Washington, DC, USA)
CAB International: Commonwealth Agricultural Bureaux International (Wallingford, UK)
CATIE: Centro Agronomico Tropical de Investigacion y Ensenanza (Turrialba, Costa Rica)
CAZRI: Central Arid Zone Research Institute (Jodphur, India)
CIAT: Centro Internacional de Agricultura Tropical (Cali, Colombia)
CREAMS: Chemicals, Runoff and Erosion from Agricultural Management Systems
CTFT: Centre technique forestier tropical (Nogent-sur-Marne, France)
D.R.S.-C.E.S.: Defense et restauration des sols-conservation des eaux et du sol
EDI: Energy Development International (Washington, DC, USA)
EPIC: Erosion Productivity Impact Calculator
EWC: East West Center (Honolulu, Hawaii, USA)
FAO: Food and Agricultural Organization of the United Nations (Rome, Italy)
FONC Project: Forest/Nature/Conservation Project (Jojakarta, Indonesia)
FR Germany: Federal Republic of Germany
GEMS (UNEP): Global Environmental Monitoring System (Nairobi, Kenya)
GTZ: Gesellschaft fur technische Zusammenarbeit (Eschborn, Federal Republic of Germany)
IAEA: International Atomic Energy Agency (Vienna, Austria)
IAHS: International Association of Hydrological Sciences (Wallingford, UK)

IBP (UNESCO): International Biological Programme (Paris, France)
IBSRAM: International Board for Soil Research and Management (Bangkok, Thailand)
ICAR: Indian Council of Agricultural Research (New Delhi, India)
ICRAF: International Council for Research in Agroforestry (Nairobi, Kenya)
ICRISAT: International Crop Research Institute for the Semi-Arid Tropics (Hyderabad, India)
IDRC: International Development Research Centre (Ottawa, Canada)
IFAD: International Fund for Agricultural Development (Rome, Italy)
IITA: International Institute of Tropical Agriculture (Ibadan, Nigeria)
ILCA: International Livestock Centre for Africa (Addis Ababa, Ethiopia)
ILO: International Labour Organization of the United Nations (Geneva, Switzerland)
ILRI: International Institute for Land Reclamation and Improvement (Wageningen, Netherlands)
INEAC: Institut national pour l'etude agronomique du Congo (Kisangani, Zaire)
IRRI: International Rice Research Institute (Los Banos, Philippines)
ITC: International Institute for Aerospace Survey and Earth Sciences (Enschede, Netherlands)
IUFRO: International Union of Forestry Research Organizations (Vienna, Austria)
NFTA: Nitrogen-Fixing Tree Association (Waimanalo, Hawaii, USA)
NIFTAL: Nitrogen Fixation of Tropical Agricultural Legumes project (Paia, Hawaii. USA)
ORSTOM: Institut francais de recherche scientifique pour le developpement en cooperation (Paris, France)
SADCC: Southern African Development Coordination Committee (Gabarone, Botswana)
SIDA: Swedish International Development Authority (Stockholm, Sweden)
SLEMSA: Soil-Loss Estimation Model for Southern Africa
TSBF: Tropical Soil Biology and Fertility programme (Harare, Zimbabwe)
UK: United Kingdom
UNEP: United Nations Environment Programme (Nairobi, Kenya)
UNESCO: United Nations Educational, Scientific and Cultural Organization (Paris, France)
UNFPA: United Nations Fund for Population Activities (New York, NY, USA)
UPLB: University of the Philippines at Los Banos (Los Banos, Philippines)
USA: United States of America
USAID: United States Agency for International Development (Washington, DC, USA)

USDA: United States Department of Agriculture (Washington, DC, USA)
USLE: Universal Soil-Loss Equation
VAM: vesicular arbuscular mycorrhizae
WMO: World Meteorological Organization (Geneva, Switzerland)

INDEX

AGROFORESTRY

AND

THE DEVELOPMENT OF TROPICAL FORESTRY

by

K.F.S. King

Nairobi

1980

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TROPICAL FORESTRY

I. INTRODUCTION

The problems of tropical land-use, of tropical forestry development, and the deforestation of tropical forests cannot be considered in vacuo. They are all part and parcel of the general development of the economies of the countries which lie between the Tropics of Cancer and of Capricorn. The difficulties that are encountered in the management and conservation of tropical forests contribute, in many cases, to the economic and social underdevelopme of tropical countries. At the same time these difficulties are caused by, and are the result of, the very state of underdevelopment The gamut of social and economic and physical factors interact with each other, and to attempt to examine any of them in isolation would be to run the risk of ignoring salient influences, of over-simplify! the issues, and of offering, for example, physical, .technological and ^scientific "iaJatiarfar":'.* that may be inappropriate, precisely because they have not taken into account the social and economic environment in which they are to be applied.

It is for this reason that the title of this pajer, Agroforesti and the Development of Tropical Forestry, has been chosen. The pape is primarily concerned with agroforestry and tropical deforestation, and its ultimate focus will be on this plague of our times. Nevertheless, because the specific problem of deforestation cannot be examined and analyzed except against the sombre background of underdevelopment, and because it cannot be prescribed for except in the context of the hopes and aspirations for accelerated development of the developing tropical countries, the paper will seek to discuss tropical deforestation as a symptom and as a cause of economic backwardness.

II. BACKGROUND

Extent and Nature of Tropical Forests

The process of assessing the coverage of the world*s forests, and the quantity, quality and regenerative attributes of the world*! forest resources is a hazardous exercise. Many of the so-called "data" which are available are suspect. It is an intriguing task to fit together the bits of information which are published, to sort out the apparent contradictions and to reconcile the conflictii opinions. The best that can be said about the figures that are presented here is that many of them have been sanctified by much use, and most have been given the imprinatur of the Food and Agriculture Organisation? the United Nations Educational, Scientific and Cultural Organisation? and the United Nations Environmental Programme.

The humid tropical forests, with which this paper is concerned, have average annual temperatures of between 24° to 27°C, yearly rainfall averages of not less than 1500 mm, and occupy an area of 1,356 million hectares or about one-third of the total forest land area of the world. Most of these forests are "natural", plantations or artificially regenerated forests covering only about 1 per cent of the total tropical forest area. The total volume of growing stock in the "closed forests" of Africa, Asia and Latin America has been assessed at 165,900 million cubic metres.

Despite the fact that about one-third of the world's forest area is occupied by tropical forests, in 1976, 77.55 per cent of the world's harvest of industrial wood was produced in North America, Europe and the USSR. North America accounted for 32 per cent, USSR for just over 24 per cent, and Europe for over 20 per cent. In the developing countries, insular Southeast Asia and East Asia were the main producers, supplying 11.2 per cent of the world's total. Africa, Central and South America, and the remaining countries of Asia and the Far East harvested 11.3 per cent, with Central and South America having the smallest share of this already paltry proportion.

Moreover, trade in tropical timber was only 15 per cent of woitAd -trade in' wood fcnd'wood products.

So much for the statistics - statistics which reveal that tropical forests are either underutilized or are mismanaged, and that this potentially valuable natural resource does not make the degree of contribution to development and to economic growth which the extent of the area it covers, and its standing stock would indicate possible.

What are the reasons for this failure of tropical forests to contribute significantly to the enhancement of human welfare in the developing countries? It is suggested that the problems of tropical forestry stem from two sources: the one biological, the other politico-socio-economic. In other words, they are a direct conseque first, of -the heterogeneity, of the mixed nature of-tbe epecies composition of tropical moist forests; and, secondly, of the fact that the moist tropical forests lie, by and large, in developing economies - in economies in which:

(a) the transport infrastructure is rudimentary;

(b) skills at the professional and technological levels are in short supply;

(c) research is unsystematic, desultory aad-Junpianned. *

(d) financial resources for development are available only at.ridiculously low levels;

(e) local technological development is often absent and therefore technology has to be imported; and,perhaps most important,

(f) there is generally a lack of knowledge on the part of political decision-makers of the enormous potential for development which tropical forests possess; and,therefore, the political will so vital for the development of this resource does not exist.

There is perhaps no need to dwell upon the nature of the heterogeneity of moist tropical forests, for this has been well documented (see, for example, Richards, 1952). The points that should be made, however, are that because there were few precedents (with respect to floristlc composition) from the temperate forests of the developed world, tropical foresters still find it difficult to evolve natural silvicultural systems through which they may predict with any significant degree of accuracy what will happen at the end of a rotation, what will be the species composition at the end of a rotation, and what will be the total stocking of individual species. In short, when operating in moist tropical forests, foresters are uncertain of the results of the application of the scientific techniques and knowledge that are available to their profession (King, 1976).

The,reason for this uncertainty, the reason for this inability to forecast with certainty the outcome of some silvicultural and management practices does not merely lie in the varied and diverse nature of the autecology of individual species, but, more important, in the fact that these species often occur in intimate mixture, and affect each other in an a lads*., infinite combination of permutations, the results of which, given present knowledge, the tropical forester is unable, generally, either to influence or predict*

The problem of the marketing of tropical hardwoods is also based, primarily, on the diversity of species that are found in. moist tropical foreets. Over the years' the opinion has been expressed that the species in this ecosystem are too many, too scattered in distribution, too uneven in quantitative occurrence, often too infrequent in distribution, for them to be marketed efficiently. As a result, in marketing mixed tropical hardwoods, esoteric systems of nomenclatural standardisation have been. attempted, complex methodologies of quality classification have been put forward, expensive procedures for the promotion of the sale of these species have been laid down, and regional and" international bureaucracies have been established. All to little avail.

This list of the ills which flow from the heterogeneity of moist tropical forests is far from exhaustive. However, it illustrates the nature of the difficulties and suggests that unless more homogenous forests are established, or unless means are found of utilising the wood from these forests in the form of pulp and ahlpB:, ; for example, the problems of tropical forestry development will remain, more or less intractable.

<u>Soils of Moist Tropical Forests</u>

There is another aspect of the problem which is central to any discussion of the development of lands occupied by moijst tronlcal forests, and that is the soil as an ecological factor in the development of tropical forest areas.

Charter (1949) has cautioned against being deceived by the luxuriance of tropical forests, for they "may conceal almost sterile soil"; and Richards (1946) has drawn attention to the < •/ -*- paradox of luxuriant tropical vegetation on leached and impoverished soils, emphasizing that there is an immense amount of nutrient material in circulation within the closed cycle of nutrients and immobilized within the vegetation itself.

Although Vine (1954) has objected strongly to the generalization that all tropical soils are poor in assimilable bases and phosphorus, / and has presented a number of examples from which he concludes that, at least for the areas of Nigeria with moderate rainfall, the maintenance of fertility presents much less difficulty than in regions of very heavy rainfall, the weight of the evidence (e.g. Reynders, 1961; Ahn, 1970; Lundgreh, 1971) indicates that the statement that a luxurious tropical moist forest' may cover an almost sterile soil still holds true (Van Baren, 1975).

In the words of the UNEP (1980), "Overview Document", "forestlands can be characterized as 'fragile ecosystems' that lend themselves to, exploitation only through sensitive application of knowledge about their dynamics. To date, man does not possess the scientific understanding - let alone the capacity to apply it - on a scale sufficient to match the complex and delicate make-up of these forests, with their potentially rich resources".

III. TROPICAL DEFORESTATION

Extent of Tropical Deforestation

It Was noted earlier that there are conflicting statistics on both the area covered by humid tropical forests, and their standing volume. It should not be surprising, therefore, to learn that there is also controversy concerning the rate at which tropical forests are being removed, and the extent of such removal. The difficulty in estimating the rate of tropical deforestation is aggravated by the fact that although, in some areas, large blocks of moist tropical forests are being logged for industrial timber, these blocks are hardly ever, if at all, clear-felled. Even If all the trees are ra»ed to the ground, the ecological conditions in the moist tropics are such that when not turned over to other forms of land-use, there is frequently natural regeneration. Cut-over moist tropical forests are therefore often in various stages of natural regeneration.

Frequently, the assessments of tropical deforestation do not distinguish between areas lost permanently to forestry and those which are going through one or other of the processes of unmanaged natural regeneration. It is true that these operations may be dysgenic in nature, but they do not necessarily result in a loss of tropical forest area. Moreover, when these types of forests are indeed distinguished, the methodology used in classifying them is often subjectively based: and the results reflect the bias of the assessor.

Data on tropical deforestation should therefore be viewed with caution, especially those which relate to areas that have been exploited for commercial timber and are expected to be left within the forest estate.

In addition, forecasts of future trends should not be initially roic?e on a global basJLs^,J^rtrtrycJLd'-wider•e-s^JLamt-es of* Trrtur-e deforestation should be aggregates of forecasts for individual countries. Even this method of forecasting, however, has its problems, for, often, there are not sufficient historical and cross-sectional data on which to make assumptions and to project trends. And again, even if such information were available, the future wood supply/demand position in individual countries, and the pressures on forest land for other goods and services might serve as countervailing factors, one way or another, in the deforestation/conservation equation.

With these limitations in mind,' the figures compiled by UNEP (1980) may be considered acceptable. In summary, UX in Central and South America, the natural tropical hardwood forests will shrink from 788 million hectares in 1975 to 562 million by the year 2000; (b) in Africa south of 'the~sajbara*:±hai natural moistt teropioalaiforeBt ^ estate will be reduced from 202 million hectares in 1975 to 187 million hectares in 2000; and in Asia and the Far East, closed natural forests will diminish in area from 291 million hectares in 1975 to 243 million hectares in the year 2000.

It should be noted that"these figures Prefer only to fores cover that is entirely reviewed once and for all, to be replaced by non-forest types of vegetation... They do not consider anything in between,e.g. disruption and degradation of forest ecosystems."

The Nature of Deforestation

It has been noted in the proceeding paragraphs that dbly a relatively small proportion of tropical forests is completely lost through their commercial e'xploitation. This, is, due. In part, to the fact that in many cases in-the fctopieal flogging ^±*c.*«l«rctive ,. and in part, to the relative ease at which natural forest regeneration of some sort or another takes place in the humid tropics.

Most of the forests that are permanently lost are transferred to agriculture. The land-use pattern is changed from forestry to agriculture either because the production of permanent or annual agricultural crops, or animal production, appears to be more profitable, or because the production of food is the dominant, the categorical imperative in a particular locality or country.

Let us consider first the allegation that is often made that either natural or artificial regeneration is too prodigal of time, that most forestry management and tilvicultural systems require longer gestation periods than most agricultural systems, and that, therefore, other things being equal, short gestation agricultural crops are to be preferred to long gestation forest crops, for both economic and financial reasons.

There is little doubt that most agricultural crops, whether annual or perennial;, have shorter gestation periods than most forestry crops, and are capable of being harvested more frequently than forestry crops. It is also evident that an investment which begins to yield earlier is superior in an objective sense to one, otherwise,equal, which has a longer gestation period. The proceeds of the quick-yielding investment can in turn be invested and a larger flow of output produced by the time that the slow-yielding one is ripe, with no loss of consumption meanwhile. This may be also true even if the slower yielding investment gives a higher return.

As we have seen the period of waiting is, of course, greater for timber than for agricultural crops, and has led to the rejection of apparently quite promising land-use proposals. Thus, in the Annual Report of the Forest Department of British Honduras for the year 1959, the following quotations from a visiting economist, Mr. J. Downle, are made: "I accept ... that the ultimate return in forestry is very large. But there is a strong prima facie presumption against a poor country investing a big proportion of its capital in a project which yields a return only after so long a period .... I do not believe that (British Honduras) can afford to wait anything from 40 to 100 years to get a return on its money. Since forestry is competing for capital with urgent needs - many of which can offer a much quicker return - the per cent rate at which a limited amount can be borrowed is not relevant; and by this standard, forestry does not pay. This conclusion is all the more true of hardwoods, where the period of investment is much longer and the true financial return is correspondingly lower."

Elsewhere, it has been suggested (King, 1965) that if the yield from the project is high enough to compensate for the long wait, it should be followed; that is, if the return from a lower yielding project, even if reinvested, will not cumulatively give the return which will result from the higher yielding project, the correct decision is to make the higher yielding investment.

This suggestion, though theoretically sound, ignores the almost daily shortage of funds in many developing countries, and begs their cash flow problems. Poverty-stricken nations simply cannot afford to wait for higher returns, even if it is in their long-term interests to do so. The tendency, therefore, is for governments to "cash" on the forest capital (the moist tropical forests) which they inherit, and if they do reinvest, to do so in schemes which guarantee the quickest possible returns.

This is the reality of one form of tropical deforestation. The developing countries need capital for the development of education, the erection of health facilities, and the establishment of the infrastructure required for the production of food and the eradication of hunger. These are all laudable-and sored aims. If a particular type of land-use retards the possible attainment of these goals, it will be rejected and other more lucrative types of land-use followed. Picus arguments about future prospects tend to be ignored in situations of immediate poverty such as most developing countries now experience, and realistic and material ways and means must be found to invoke the political will necessary for the arrest of deforestation and the reclamation and rehabilitation of deforested areas.

The largest loss of tropical forests is due however, to the transfer of forest land to food production. And this is done in several ways. First is the method of shifting cultivation which traditionally involved communities with strong historical, social and economic roots in the forests. The custom and knowledge of the development of both crops and trees which these communities possessed, ensured a relatively stable balance with the ecological environment. Moreover, the relatively low intensity of the populations which the system supported almost always permitted the resuscitation of the soil before the cultivators returned to a fallow area.

Today, throughout the world, the practice of shifting cultivation is changing rapidly. In most cases, the changes have been induced by demographic factors such as increased population growth rates and migration. In some instances, the policies of governments have led to a reduction of the area of land available for shifting agriculture. Whatever the reasons, the available area per unit family has been considerably reduced, there is continuing destruction of more and more forests, the fallow periods.have been drastically shortened and soils are not allowed the necessary time to be rehabilitated.

The second area in which forests are lost to food producers is in the creation of settlements. In Asia, Latin America, and Africa the general failure of food production to keep up with increasing demand has led to serious attempts being made to achieve this objective either through increased food productivity per unit of land, or through increasing food production by putting new lands under agriculture.

Much of these new lands comes from the tropical forests and here again, it might be argued that proper knowledge and foresight would force governments to keep the landless peasant away from these fragile ecosystems. However, here again such special pleadings would ignore the realities of the situation in many developing countries.

It is true that during the last two decades or so, there have been remarkable advances in tropical agriculture. Indeed, according to some (see e.g. Borlaug, 1971; Dalrymple, 1972), the progress which has been made in the development, dissemination and adaptation of the new agricultural technology has been unprecedented. This "green revolution" has been based primarily on the development of high-yielding crop varieties and on the intensification of the principles of plantation agriculture.

Unfortunately, the high .-yielding crop varieties that are being promoted for use in the tropics seem to require costly inputs of fertilizers, water, pesttifcldas and energy* which flaw -- developing countries are able to afford to the extent necessary. Moreover, the areas which are generally and correctly identified by tropical agronomists as being suitable for the growth and production of these high yielding cereals do not comprise the bulk of tropical land. In these and other reasons, these types of agriculture have not expanded rapidly enough, significantly to reduce the number of people in the developing world who are forced to depend for their very existence on food that is produced, for example, in the humid forest areas of the developing world.

The people who live in these areas are, on average, poorer than those who live in other parts of their already poor countries. They are thus the poorest of the world's poor. They cannot afford to purchase food from other less brittle and fragile ecological zones. Accordingly, if they must eat they must either be given "food aid", or be made to settle in areas that are better suited to permanent arable agriculture, or be given alternative occupations so that they might earn money to buy food, or produce food for their sustenance in these fragile ecosystems (King, 1979).

None of the possibilities listed in the last paragraph is universally applicable and viable. "Food aid" is essentially an emergency measure, or should be. Resettlement is costly and bedevilled by a number of social problems which have led to many failures. Job creation is difficult in the developing economies, which on average, acknowledge a rate of unemployment of 25 per cent. There are few alternative sources of income or food for many of the people in the developing countries. Many of them therefore have to resort to the forests to provide food for themselves and their families.

Tropical deforestation is therefore a consequence of economic deprivation. Solutions which ignore this basic fact are doomed to failure. Forests are commercially exploited to raise money for essential development. Forests are converted to agricultural cash crops because it appears to make both economic and financial sense to do so. Forests are farmed by shifting cultivators and settlers because they **need** land for food for their very existence, and because no acceptable alternatives are provided by governments and by the international technical assistance community.

Another cause for the rape of tropical forests is the quest for fuelwood for cooking and heating, and for poles for shelter. In 1975, when 2,431 million cubic metres of wood were harvested from the world's forests, 1,182 million cubic metres (or nearly 49 per cent of the total volume removed) were utilized for fuelwood, Eighty-six per cent of this fuelwood was removed and consumed in the developing countries and tropical regions of Africa, Central and South America, and Asia. About 90 per cent of the wood which was harvested in Africa, 82 per cent of that in Central and South America, and just over 73 per cent of that which was felled in Asia and the Far East was utilized for firewood.

The rural areas of most of the developing countries are almost totally dependent upon non-commercial organic fuels for cooking, heating, agricultural processing and industry. They cannot do without this wood - and so they assist in the deforestation of the tropics.

We have therefore a paradoxical, contradictory situation, in which the very needs of the people compel them to over-exploit a resource which they will need always, or at least in the foreseeable future; a resource, the very existence of which influences not only the lives of the exploiters, but those who occupy areas sometimes far removed from those that have been ravaged.

The Consequences of Tropical Deforestation

Forests are the greatest achievement of ecological evolution. They are the largest most complex, and most self-perpetuating of all ecosystems. It is in the forests that natural regulatory processes excel, producing the most stable of all ecosystems (Smith, 1970). It is the forests which possess the most diverse gene pool - both for plants and for animals.

The most important properties of the earth's surface which influence climate, and which human activity can influence, are reflectivity, heat capacity and conductivity, availability of water and dust, aerodynamic roughness, emissivity in the infra-red band, and heat release to the ground (Wilson, 1970).

In all these aspects the forests are important. The reflectivity of the forests is low because of the high light absorptive capacity of their green leaves when converting radiant energy to chemical energy. Indeed, it is well established that densely built up areas and deserts, as well as grassland, have a higher albedo than forests, and that a unit increase in the earth*s albedo will cause a decrease in average surface temperature of 1.8 F (XJ.Sihi Congress, 1972). In an interesting experiment in the early 70's, two integrations of a global general circulation model, differing only in the prescribed surface albedo in the Sahara, showed that an increase in albedo resulting from a decrease in plant cover causes a decrease in rainfall. Thus, any tendency for plant cover to decrease would be reinforced by a decrease in rainfall, and could initiate or perpetuate a drought (Charney, Stone, and Quirk, 1975).

Moreover, because large amounts of latent heat are fixed during the evapotranspiration process, the capacity of the forests to absorb heat is high. * In contrast, forests have a low heat conductivity, because their thick and complex structure prevents rapid cooling or heating, and regulates the heat released to the ground.

Also, there is little doxibt that forests regulate water supplies by restricting run-off during peak rainy periods, and releasing water through springs and rivers during the dry seasons. Thus, thetfetil amount sf.water'available for use may be-significantly increased through its release from the forests in those seasons when it is most needed.

In addition, forests, by acting as windbreaks, create aerodynamic roughness and assist in arresting dust particles. Their emissivlty of the infra-red band is also very high. It is evident, therefore, that the forests play roles which affect all the important factors which influence climate.

'Forests also affect the composition of the atmosphere. Green plants are the only organisms capable of converting radiant energy from the sun imto .-chemical energy. During this process of photo.--synthesis, carbon dioxide is assimilated and oxygen is released. The total rate of net photosynthesis is estimated to fix nearly 80 billion tons of carbon per year. When it is realised that nearly half of this process occurs in forests, their significance as atmospheric purifying agents would be clearly appreciated.

Forests, therefore, are one of the climatic buffers on which mankind depends - a buffer which, because of its complex organic structure, is able to withstand somewhat severe perturbations of its physical environment, provided that the changes and stresses to which it is subjected are not pushed beyond a certain threshold (Odum, 1S69).

On top of all this, the unique physiognomy of the forests, together with their litter and humic layers, minimises compaction by rainfall of the forest soil, and protects the earth against erosion. Thus, the presence of forests in critical areas, reduces the possibility of the siltation of rivers and of reservoirs, effectively prevents the denudation of countrysides, and contributes significantly to economic activities in the valleys beneath and adjacent to them.

It is evident therefore that widespread tropical deforestation can impose severe stresses on the ecosystem, and can influence adversely the welfare of mankind now and in the future.

But the problem, as this paper has tried to emphasize, is not simply one of arresting tropical forest degradationJor of restoring forest cover «>n-areit» £tt which, they:axe--most required* _>Mc>3t goye-rnmsnt3 would do these things if they could afford to do so. And most tropical farmers would desist from felling tropical forests, from shifting from area to area each year or two, from seeing their agricultural drop yields drop, as soil fertility diminishes, from sufferirxg from periodic floods and droughts,.if they were offered viable alternatives.

This analysis of the contribution of forests to life is based on King (1976a)

We must therefore attempt to evolve a system which would reduce the costs of forest plantation establishment, which would ensure that the protective cover of forests in the tropics is maintained and/or restored, and which would, at one and the same time, permit forest land to be utilised for the production of food and/or the rearing of animals. In short, a system which produces as it conserves. Such a system is agroforestry*,

IV. CONCEPTS AND PRINCIPLES OF AGROFORESTRY

Definition ,

Ag'roforestry has been defined as "a sustainable land management system which increases the yield of the land, combines the production of crops (including tree crops) and forest plants and/or animals simultaneously or sequentially, on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population" (Bene et al 1977; King and Chandler, 1978).

An attempt has been made elsewhere (King, 1978) to expand the definition, and to distinguish various sub-divisions of agroforestry.

Agroforestry is a genetic term which embraces the following components:-

Agri-silviculture - the conscious and deliberate use of land for the concurrent production of agricultural crops (including tree crops) and forest crops.

Sylvopastoral systems - these are land management systems in which forests are managed for the production of wood as well as for the rearing of domesticated animals. It should be noted that in this system the animals are kept and permitted to graze within the forests. Sylvopastoral systems should therefore be distinguished from systems in which forage (either herbaceous or shrubby) is grown in mixture with forest trees. These latter systems are properly agri-silvicultural systems.

Agro-sylvo-pastoral systems - systems in which land is managed for the concurrent production of agricultural and forest crops and for the rearing of domesticated animals. This system is, in effect, a combination of agri-silviculture and the sylvo-pastoral system.

Multipurpose forest tree production systems - here forest tree species are regenerated and managed for their ability to produce not only wood, but leaves and/or fruit that are suitable for food and/or fodder.

In all agrof ores try land managemen-t—eyeteme -there—are-two essential and related aims: the systems should conserve and improve the site, and at the same time optimise the combined production of *a* forest crop and an agricultural crop.

<u>Analogy between mixed cropping and agroforestry</u>

"Agroforestry? , may;,be-:cDmpared..in.concept^with-cfciie "multiple cropping" systems of agriculturists that have become increasingly popular over the last ten years on so. Thus the term "multiple cropping" will be the generic term, comparable in many respects to "agroforestry".

The term "mixed' cropping" might be considered to be similar to that of "agrisilviculture" as I have defined it, or as Deets (1978) has defined "mixed cropping" - the growing of more than one species on-the same piece of land at the same time. The spatial arrangements of the crops in "mixed cropping" systems or in "agri-silvicultural" systems might be <u>haphazard</u> or might be <u>organised</u>.

Haphazard systems in agriculture are often found in Africa and Latin America. In these a seeming multiplicity of agricultural••.;•. species is grown in mixture. The species appear to have been chosen because their several root systems tap different layers of the soil for nutrients and water, because they possess different solar energy requirements, because they simulate the many-storeyed physiognomy of natural tropical forests, and because in general the species comple-. ment rather than compete with each other.

Exact parallels of the haphazard "mixed cropping" systems of agriculture are difficult to find in "agrisilviculture", but the practice in Kenya, for example, of having patches of annual crops interspersed with patches of forest tree crops, which together form forestry agrisilvicultural mosaics might be considered 'to be similar" in many respects to the "mixed cropping" systems of the agriculturists.

The organised systems of mixed cropping in agriculture are normally referred to as "intercropping" or "row-intercropping" systems. In these, of course, the different species are grown in rows and the populations of each are fixed. This is similar to the traditional "agrisilvicultural" systems of the foresters, except, of course, that the forest trees are intercropped with agricultural species. It is suggested that the categories of "agrisilviculture" are not closed and that in addition to having single rows of trees intercropped with rows of agricultural crops it might be beneficial on some sites and for some trees and agricultural species, and under some socio-economic conditions to have several rows or strips of trees that are intercropped with several rows of agricultural crops. The system might also be expanded to include the transfer of litter and/or lopped branches from the strips of forest trees to the agricultural crops to provide a woody mulch.

To extend the analogy between multiple cropping agricultural systems and agroforestry still further the "sequential cropping" systems of agriculturists, in which more than one crop is grown on the same piece of land at different times of the year, might be likened to the planned fallow of agroforestry in which forest land is cleared and cultivated and then tree species, chosen mainly for their rapid soil ameliorating soil characteristics, are established when agricultural yields become unacceptably low. These trees are in turn felled after the original soil.fertility is restored or improved, and the sequence is continued. In short,"sequential cropping" in agroforestry is a system of planned fallow that is designed to control and harness shifting cultivation, and to reduce the fallow period without deterioration of the site.

The analogy between "multiple cropping" systems and "agroforestry'[1] systems may be pursued even further. It is suggested, however, that enough has been now said on this aspect of the subject to demonstrate that the principles and concepts of agroforestry might not be wholly unintelligible to agricultural scientists, and that the forester might learn a great deal from the research which has already been conducted on intercropping systems by agricultural scientists. In other words, attempts must be made to break down, to eschew, the false dichotomy of agriculture and forestry.

Competition

The basic problem in agroforestry systems is that of competition. It might be useful, therefore, to examine in general terms the issue of competition among plant species - for it is important that the influence- of' ^the-tree crops on-5the agricultural, crops,.a&d vice versa do not adversely counteract the positive influences of the forest ecosystem. In other words, it is necessary to ensure that competition among the different components of the system is not great enough to affect the total productivity of the system in an adverse manner.

Clements et al., (1929) have described competition as a purely physical process. The authors state that "with few exceptions, such as the crowding of tuberous plants when grown too closely, an actual struggle between competing plants never occurs. Competition arises from the reaction of one plant upon the physical factors about it and the effect of the modified factors upon its competitors. In the exact sense, two plants, no matter how close, do not compete with each other so long as the water content, the nutrient material, the light and the heat are in excess of the needs of both. When the immediate supply of a single necessary factor falls below the combined demands of the plants, competition begins".

Donald (1963) has expressed the same principle in another way: "Competition occurs when each of two or more organisms seeks the measure it wants of any particular factor or thing and when the immediate supply of the factor or thing is below the combined demand of the organisms".

Both Clements (1929) and Donald (1963) have stressed that competition for space is exceptional, and that what are really important are water, nutrients, light, oxygen and carbon dioxide. In the reproductive phase, the agents of pollination and dispersal are of course important. Temperature and humidity which also affect growth, are not commodities in finite supply and therefore are not the subject of competition.

Water, nutrients and light are the factors most commonly in short supply, and it is these that will be borne in mind in the discussion that follows. However, it is perhaps apposite at this stage, before referring specifically to the agroforestry requirements, to emphasize the following:

(a) "Most of the factors for which there is competition are found as a pool of material from which competltdrs draw their supplies. If the pool is of limited volume, or it ijt subject to intermittent depletion by the competing plants, then the successful competitor is the plant which draws most rapidly from the pool or which can continue to withdraw from the pool when it is at low ebb or when its contents" can no longer be tapped by other plants. If all the plants in the community are nearly equal in competitive ability .... they will tend to share equally in its upply until it is exhausted, and then, simultaneously, to suffer the effect of depletion of the pool". The foregoing applies chiefly to water.

(b) With respect to nutrients, "the capacity to draw from the pool is in varying degree an expression of the differing ability of plants to make use of the :nutrient in different chemical and physical forms".

(c) The concept of a "pool" is not applicable, is not valid, when competition for light is considered. "There is no store of light energy in the immediate environs of the plant ... Light is available as a passing stream which must be intercepted by the leaves if it is not to be permanently lost to the plant. A dense canopy will intercept all light, but the young crop characte-ristically covers only a small proportion of the soil surface and most of the energy is absorbed or reflected by the soil" (Donald, 1963> .

A general conclusion may be drawn from this simplified analysis of the important factors and processes in plant competition, with respect to agroforestry. As far as possible, the forest and agricul-tural species that are utilized in the system should be compatible and should complement each other in growth patterns over most stages of their lives. More specifically, with respect to water they should be unequal in competitive ability; with respect to nutrients, they should vary in ability to utilize the nutrients in different forms; and with respect to light, those species should be selected that display growth patterns, rates of growth, phenology, and architecture that permit maximum interception by both the agricultural and forest crops at any one time, but that also minimize competition between the two groups of crops at all stages of their growth.

Elsewhere (King, 1979), the characteristics of the tree species that should be grown in agroforestry systems have been listed:

- they should be amenable to early wide espacement;

- they should possess self-pruning properties;

- if not self-pruning, their phbto^ynthetic efficiency . ; ' should not significantly decrease with heavy pruning;

-/ they should have a low crown diameter-to-bole diameter ratio , i.e. the vidth of their crowns should be small relative to bole diameter;

- they should be light-branching in habit;

- they should be tolerant of side-shade, if indeed not of full over-head shade in the early stages of growth;

- their phyllotaxis should permit the penetration of light to the ground;
- their phenology, particularly with respect to leaf flushing and leaf-fall, should be advantageous to the growth of the annual crop In conjunction with which they *Hey are being raised;
- their rate of litter fall and litter decomposition should have positive effects upon the soil;
- their "above ground" changes over time in structure and morphology should be such that they retain or improve those characteristics that reduce competition for solar energy, nutrients and water;
- their root systems and root growth characteristics ideally should result in the exploration of soil layers that are different from those being tapped by the agricultural species; and
- they should be efficient nutrient pumps.

This list of characteristics of the ideal tree species for use in agrisilvicultural systems is not exhaustive, but it indicates the principles that should be followed in the selection of such *r.* ... *s* speeMit.-.In addition, cognisance must be taken of the known responses of the tree species to various management practices (such as pruning, thinning, and coppicing, for example) and to individual tree and stand manipulation. The same procedure should be followed with respect to the agricultural crop component of the system.

Put in another way, the plant architecture and morphology, the phenology of woody perennials, and the root distribution, root growth and root activity of the trees, must be examined. Moreover, assessments must be made of those factors that affect net carbon fixation with respect to such factors as species differences, differing source/sink situations for annuals and perennials, and leaf and plant ageing.

In addition, the influence of genotype and environment on dry matter distribution in herbaceous and woody plants; the effects of management on plant growth, dry matter distribution and plant development; and the factors affecting the plant's nutrient needs and the distribution of nutrients within plants should be examined.

Although there is very little information regarding competition in agroforestry systems per se, it must not be imagined that no knowledge exists that is applicable to competition in agroforestry systems, with respect to conventional agriculture and conventional forestry. This is not the place to review the prodigious volume of literature extant, but Iwaki's (1959) work on interspecific competition in plant communities', Hall's (1974 and 1974a) and de Wit's (19G0 and 1963) work on the nature of interference between plants of different species; the analysis of Trenbath and Angus (1975) on the relationship of leaf inclination and crop production; Grime's (1966) investigations on shade avoidance and tolerance; and the studies of Puckridge and Donald (1967) on competition among plants sown at a wide range of densities, give but a small proportion of the knowledge already available and that can be used with advantage in the **practise** of agroforestry, in the formulation of research policies and in the design of research projects in agroforestry. More important in the context of this paper, they indicate the concepts that may be applied to agroforestry systems. It is also possible to construct predictive models that would suggest the probable responses of plants in various mixtures and combinations in agroforestry systems (Trenbath, 1974 and 1978).

V. AGROFORESTRY IN PRACTICE

The practice of one form or another of agroforestry is so widespread that it would not be possible in a paper such as this to describe in detail all the ramifications of this type of land management. Surveys conducted by King (19'68) and by the Interna-*' tional Council for Research in Agroforestry (ICRAF) in 19 78 indicate that the system is followed in all the developing regions in about 100 developing countries.

Practices range from the establishment of large scale forest plantations to the employment of the system is small farm holdings and woodlots. They cover the intercropping of both softwood and hardwood forest species with annual and perennial agricultural crops, as well as forage species. And they embrace the grazing of animals in the forest.

Not surprisingly, the forestry species that are utilised, and the cultural practices that are followed vary from region to region, from country to country, and even within countries. Moreover, although the system when consciously practised is most frequently concerned with plantation forestry, in a few areas there are remarkable variations from this norm. Thus, in Sierra

Leone, after the first brushing by the farmer, saplings, poles and seed trees of valuable species are marked for retention. The area is then clear-felled (except;for tha.marked trees which'are ring fire traced) and burnt. Selected tree species are planted throughout the farm on a wide espacement of 60 feet between the lines, and 30 feet between the trees. The secondary growth which succeeds the cultivation provides a filler crop between the planted lines. Clearing operations are required, but thinning is greatly reduced. The objective is "natural forest" with a high percentage of valuable timber (Sawyer, 1965).

What follows is a somewhat rapid survey of certain important practices and customs in order to give some idea of the wealth of information that is available, of the need to systematise this information, and of the necessity to conduct research in order to axtend the frontiers of the various systems of agroforestry.

Time and sequence of planting

The one aspect of agri-silviculture that is common to most countries is that the system begins with the clear-felling and burning of either the remains of recently exploited forest or secondary scrub. After burning, however, the subsequent operations vary considerably from country to country. In most countries the first agricultural crops are planted before the tree crop, in about a third after the tree crop, and in a very small proportion the agricultural and forest crops are planted at the same time.

Nor are these the only differences. In those areas in which the agricultural crop is planted first, the period between the initial planting of the agricultural crop and the planting of the trees ranges from as long as five years to as little as a few weeks. Where, however, the forest species are planted first, the time which elapses before the agricultural crop is planted is generally only a few months.

Forest species

Acacia,albida
A. arabica
A. catechu
A. decurrens
A. nilotica
A. Senegal

Ailanthus excelsa
0 „ , „„
7*XJbizzJ£ iebbeck
A.yprocera
Anthocephalu s^cadamba
Aucoumea^klaineana
Auracaria^angustlfolia
Azadirachta.»lndica

Bambusa spp
Bauhlnia racemosa
'Betula spp.
Bombax spp.
Boswellia serrata
Buckland!a populnea
Canariun spp.
Carpinus spp.
Cassia siamaea
Casuarina spp.
Cedrela mexlcana
£. odorata
C. toona
Chlckrassia tabularis
Cordia alliodora
Cunninghamia lanceolata
Cupressua spp.
Dalbergia slssoo
Dendrocalamus spp.
Dipterocarpus spp.
Docynia spp.
Durlo zlbethings
Entandrophragma angolense
E. cylindricum
E. macrophyllum
E. septentrionale
Eucalyptus spp.
Gmelina arborea
Hardwickia binata
Hevea brasilionsis
Hibiscus elatus
Hopea adorata
Intsla palembanica
Juniperus procera
Khaya grandlfoliola
K. ivorensis
Kydia calycina
Lagerstroemia flosregina
Lannea grandis
Leucaena leucocephala
Lovoa trichilioides
Michelia spp.
Morus spp.
Nauclea diderichil
Peltophorum ferrugineum
Pinus caribaea
P. elliottli
P. insularis
P. patula
P. radiata
P. sylvestis
P. taeda
Populus spp.
Propopis spp.
Prunus puddum
Pterocarpus dalbergioides
Quercus borealus
2.* rokur
Roblnia spp.
Salmalia malabarica
Sesbanea spp.
Shorea gysbertsiana
5. robusta
Swietenia macrophylla
Tabebuia pentaphylla
Tarrittia utilis
Tectona grandis
Terminalia ivorensis
Tf» superba
Triplochiton scleroxylon
Zizyphus incurva

Espacement

In the vast majority of countries the spacing of the tree crop is the same as that which would be normally employed if the plantations were being established without agricultural crops. In e few cases the spacing adopted under the system of agrisilviculture is closer than normal. In these instances the avowed object of this closer espacement is early crown closure, in order to limit the use of the land for agricultural purposes. In very few countries are wider espacements employed in order to permit longer use of the land by cultivators, although in the past, the planting of tree crops with bananas in Zaire led to somewhat aberrant espacement.

Agricultural Crops

The agricultural species that are grown in conjunction with the forest trees are many and varied, and are generally chosen because of the agricultural and feeding habits of the cultivator, rather than because of their possible effects on the tree crops, or their possible resistance to competion from the tree crop, e

Amaranthus spp.	Coptis japonica
Anacardium occidentale	Cucumis sativa
Ananas commosus	C. melo/Citrullus vulgaris
Anthyllis vulneraria	Cucurbita maxima
Arachis hypogaea	C. pepo
Artocarpus integrifolia	Curcuma longa
Avena sativa	Dioscorea alata
Bixa olerana	D. rotundata
Boehmeria nivea	D. cayanensis
Brassica spp.	Eleusine coracana
Cajanus cajan	Elettaria cardamon
C. indicus	Glycine soya.
Capsicum spp.	Gossypium hirsutum
Carica papaya	G. arboreum
Chrysanthemum cinerariafolium	Hevea spp.
Citrus sinensis	Helianthus annuus
C. limon	Hibiscus esculentum
C. paradisiaca	Hibiscus sabdariffa
Citrus spp.	Hordeum vulgare
Coffea spp.	Ipomoea batatas
Colocasia antiguorum	Lactuca sativa
C. esculentum	Linum usitatissium
Collybia shiitake	Lycopersicon esculentum

Manglfera indica
Manihot utilissima/M. esculentum
Medicago sativa
Musa spp.
Nicotiana talacum
Oryza sativa
Oximum basilicum
Panicum miliaceum
Passiflora edulis
Pelargonium graveolens
Pennisetum typhoideum
Phaseolus spp.
Polygonum odoratum
Portulaca oleracea
Psldlum guajava
Ricinus communis
Saccharum officinarum
Secale cereale
Sesamum indica
Setaria italica
Sclanum melongena
S. nigrum
S. rotundifolium
S. tuberrosum
Sorghum vulgare
Thea sinensis
Theobroma cacao
Triticum vulgare
Vigna sinensis
V. unguiculata
Voandzea subterranea
Xanthosoma sagittifolia
Zea mays
Zingiber officinale

Cultural Practices

It will have been noted that the list of forest species ranges from trees to bamboos, and from the conifers to the broad-leaved, it includes shallow-rooting species as well as deep-rooting species; narrow crowned species are represented and so are those with a high crown-diameter/bole-diameter ratio; it includes species which will not tolerate suppression at any stage and some which do best with a certain amount of shade.

The truth is that most of the evidence which we now possess with respect to the growth of agricultural crops in conjunction with forest crops is confined to the initial stages of growth, to the period between planting out and canopy closure, to the establishment period of the first crop. Almost any combination of species can be grown together at this stage, for competition in the clements-oian sense is non-existent. It is when the trees increase in size and their roots spread, when their crowns touch or come near to touching, in short when the forest plantation is established that effective competition for nutrients, for water and for solar energy begins.

Unfortunately there is very little evidence, from forestry per se, about what occurs when the plantations reach this relatively advanced stage of their lives. There is evidence of what happens before canopy closure, and the general conclusion is that there is no reduction of the growth of either the tree or agricultural crop (Eirand and Catinot, 1S61; Georgopoulos, 1959); and Kraevoj e_t. al., 1956; for example), and in some cases there is even an increase in growth of the tree crop (Ogbe, 1967; Shebbeare, 1921).

If the farmer is to be allowed to remain longer in the forest plantations, the trees should be planted out at wider espacements, there should be provision for early mechanical thinnings of the plantations either immediately before or at the time of canopy closure, and prunings or loppings of varying intensities should Me performed. These cultural practices will no doubt not only reduce the onset of the competitive stage, but will also, once it is reached, reduce actual competition.

Although, as has been stated, there have been no reports of research on the effects of thinning and pruning on the growth of the associated crops, observations at Kijabe in Kenya, for example, support the view that relatively small gaps in the forest canopy might give rise to conditions favourable to agricultural production. There, in several compartments, there was sporadic failure of trans-plants at the time of "planting-out", No "beating up" was undertaken. Now 10 to 15 year old plantations of *Eucalyptus* spp. with gaps in their canopies are intercropped by local farmers who report that there have been no reduction in their yields since the establishment of the plantations.

Economics of Agroforestry

It will be recalled that when discussing the economics of forest plantation establishment, it was pointed out that because of the relatively long gestation periods, and because no financial returns were obtainable for relatively long periods after establi-ment, several plantations tended to be considered to be uneconomical and did not attract the required investment.

Forest plantations that are established under some form of agroforestry land management overcome this difficulty, for returns are obtainable from the agricultural crop in the first years of the plantation's life and would offset, to some extent, the economic difficulties of the long waiting period.

In addition, if a system were adopted of planting for the first years annual agricultural crops, then following these with perennial crops such as cocoa, coffee, bananas and plantains, there would be returns for most of the rotation of the forest plantation.

Moreover, as Nair (31979) has so clearly demonstrated, tree crops established in the manner normally followed in most forestry operations do not utilise available nutrients, water and solar energy efficiently in the early stages of the plantations growth. Accordingly, the phased intercropping of these plantations with suitable food species and cash crops would greatly increase the economic viability, and Investment possibilities of arresting deforestation and reclaiming deforested land in the tropics through reforestation.

The available evidence also suggests that acceptable financial returns are obtainable in those cases where agroforestry is conducted because of land pressure. Thus, Srivastava and Pant (19 7 9) have demonstrated that financial internal rates of return of up to 89 per cent have been realised in farm forestry projects in Gujarat, and that these were a marked increase over the returns obtained from his seasonal crops. Moreover, the financial rate of return surpassed "any other fair market investment". In addition, the employment generated was significantly greater than other comparable activities.

Olawoye (1974) reports as follows from Nigeria: "Of great importance is the income-generating capacity of agrisilvicultural schemes. Under 'departmental agrisilviculture' where the participants are direct employees of the Forest Department, a minimum salary of N720 per annum is paid to each unskilled labourer. Under 'traditional agrisilviculture' profits accruing to each farmer range from about N100-N400 annually with a mean of about N210. The two sets of income considerably exceed, the average per capita.' income of about N90 in the agricultural sector of the economy.

"The participants of the schemes are generally aware of the significant improvement in the growth of the rural economy. Out of the total 2,000 farmers interviewed, 13 per cent pointed put that they were able to afford their house rents more conveniently because of farming in the reserve. Thirty-three per cents of the respondents said that their participation in the agrisilvicultural scheme increased their purchasing power; 14 per cent were abl.o to pay their taxes readily, and another 14 per cent got enough money to undertake petty trading."

These data are only indicative and should not be used as an absolute justification for agroforestry schemes. Nevertheless, they do suggest that agroforestry might provide one means of combatting tropical deforestation.

Institutional Requirements

If agroforestry is to be successfully practised in the forest reserves and the villages of tropical developing countries there would be fundamental attitudinal adjustments by farmer, forest dweller and forester, and for reaching institutional changes in those areas of government which impinge on tropical land-use.

In many parts of the tropics there is an absence of a "foresttyv tradition" among the farming communities, which contrasts with a usually deeply founded tradition of agriculture. The forest is often seen as an obstacle to development, and the services which it provides are sometimes not appreciated.

The forester, on the other hand, through his education and through the forest laws which he is called upon to enforce, has been led to believe that people are an impediment to the development of his forest estate. The forest is his domain. Farming and other "no-forest practices" must be kept out of the reserves. The forest laws of most developing countries enshribe this debilitating concept.

There therefore exists two psychological forces which restrict development, and which contribute not only to deforestation but to the failure to reforest after deforestation: the attitudes of the farmer, and the prejudices of the forester.

It is not easy to prescribe for psychological, for attitudinal change. However, it has been argued with some truth that if the economic benefits are demonstably . great -e-aougbv jattitodes . waulxLu. change. An attempt has already been made in this paper to show that the economic returns to the farmer and to the forester from agro-forestry systems of management are, in many cases, higher than those which would accrue in pure, classical forestry situations, and in areas in which the farmer is forced to work in marginal ecological conditions and in situations of land hunger.

It has also been argued, again with some validity, that the presence of an efficient and relevant institutional structure would assist in the changing of attitudes.

If agroforestry systems are to be "people oriented", and this is the very basis of the systems, the <u>Extension Services</u> should be established in the Forestry Departments of the developing world. These services should be staffed by personnel trained in forestry and in the communication arts. Their duties should include not only the dissemination of information and techniques relevant to forestry and agroforestry systems, but perhaps more important, they should be urged to inculcate the habit of listening to the farmer, of understanding his problems, of appreciating hi-s hopes and aspirations, and of profitting from the techniques and practices which he himself has evolved and empirically tested.

<u>Training</u> in forestry at all levels, should be systems-oriented, and the forester should be educated to think of himself as a land manager. The basic tenets of agriculture should be taught, as should be the agronomy of those agricultural species that are utilised in the areas in which he works. In India and in Nigeria, for example, there is some evidence that some" agroforestry schemes have not given the returns of which they are capable simply because the most suitable agricultural techniques were not followed.

The laws of forestry which prevail in most developing countries should also be seriously analysed and, if necessary revised. Most of the forest laws that are extant are restrictive and punitive in intent; were conceived and enacted at a time when land was in relatively great supply; and contain reservation clauses which were formulated without benefit of land capability assessment and land-use studies. Moreover, as has been emphasized before,-they deliberately exclude consideration of the farmer and the forest worker, and, perhaps unconsciously, fail to appreciate how these omissions might lead to the deforestation of the very forests the laws were designed to protect.

Modern forest laws should be "people-oriented" and biased in favour of development. This is not to say that the services which the forests provide, jind the nurturing role which they play should k'-t be disregarded. What is being urged is a judicious blend of production and conservation, in order, paradoxically, that essential forest cover might be retained.

'.The analysis in this section of this paper has been confined, r.imost exclusively, to agrisilvicultural systems. Silvopastoral system and the role of multipurpose trees have been virtually ignored. In a paper such as this, it is difficult to cover all aspects of agroforestry, and only the underlying principles and prospects can be exposed. The concentration on agrisilvicultural systems was intended to illustrate these principles and prospects which are relevant to the gamut of agroforestry systems.

VI. SUPPORTING MEASURES

It is not intended to give the impression that agroforestry systems are the answer to all the problems of tropical forestry aeveiopment, or that solutions to all the difficulties of agroforestry are known. Ear fromiit. Agroforestry is essentially a low-input system that is designed for those ecosystems that are fragile. Moreover, the circumstances for its successful application appear to be most suitable in socio-economic conditions that are marginal or sub-marginal.

Much research needs to be conducted on, inter alias

(i) the testing of the shade tolerance of agricultural species;

(ii) the identification of forest species which protect the soil but do not reduce energy levels on the forest floor;

(iii) the ascertaining of optimum espacements of Loth agricultural and forest crops under different ecological conditions;

(iv) the investigation of optimum species (agricultural and forestry) combinations;

(v) the design of thinning regimes to optimize the yields of both the tree and agricultural crop; and

(vi) the design of pruning and lopping regimes for the same purpose.

In addition, the following fundamental studies must be undertaken to underpin the field work described in the previous paragraph and to provide eventually a body of basic principles. Studies of:

(i) the dynamics of the various nutrient cycles which occur when the forest is cleared, during the cropping period, and during fallow;

(ii) the allelopathy >hd complementarity of various species;

(iii) the competition for solar energy among trees and between trees "ud agricultural crops;

(iv) the morphology and physiology of various tree species,-

(v) leaf production and leaf fall of particular species and the influence of their occurrence or competition for solar energy and the nutrient cycle.

Moreover, new breeding schemes should be designed to obtain those characteristics that are considered necessary for successful and efficient intercropping.

In addition, as has been pointed out, there is a range of socio-economic-institutional studies which must be made in order to ensure that the people, for whom the system is designed, ultimately benefit.

Such research, becuase of its very nature, should not be haphazard and unplanned, but needs to ^e institutionalised and well-funded. And much of it has to be undertaken in different parts of the vropics.

It is also desirable that it be undertaken within the context of general forestry research that is geared to the arrest of tropical deforestation, and to the rehabilitation of critical areas that have already been deforested or are without forest cover.

Accordingly, it is suggested that under the aegis of an organisation such as the Consultative Group on International Agricultural Research (CGIAR), or a similar agency, a fund be established for tropical forestry research and development. Such a fund could provide the finances necessary for a central co-ordinating research organisation, which would establish a global network of research stations and would utilize existing forestry research institutions wherever-possibles-

Many of the recent advances in tropical agriculture have occurred because of such an approach. It is submitted that the problems of tropical forestry and tropical deforestation are no less important, and no less intractable than many of the problems of tropical agriculture. Accordingly, serious attempts should be made to obtain the requisite funding and to establish the necessary research capability.

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