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AGROFORESTRY FOR SOIL CONSERVATION

ANTHONY YOUNG

C·A·B International

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International Council for Research in Agroforestry

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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.

Björn 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 Köppen 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	Köppen 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, lacking 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 (FAO/UNESCO, 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

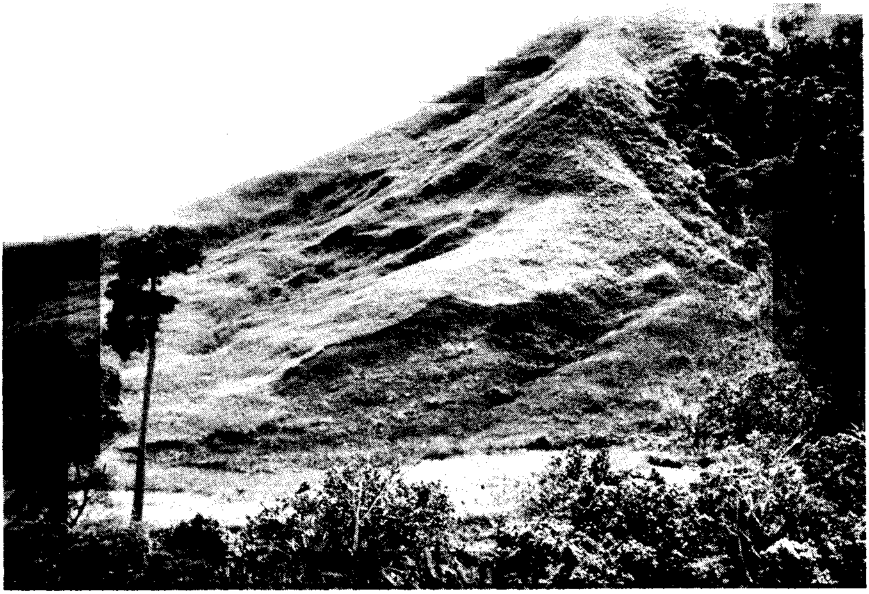
Evidence from direct experimental observations on erosion under agroforestry systems is limited. As in most branches of agroforestry research, however, there is much to be learnt from taking the results of research based on agricultural and forest land use and applying them to agroforestry.

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

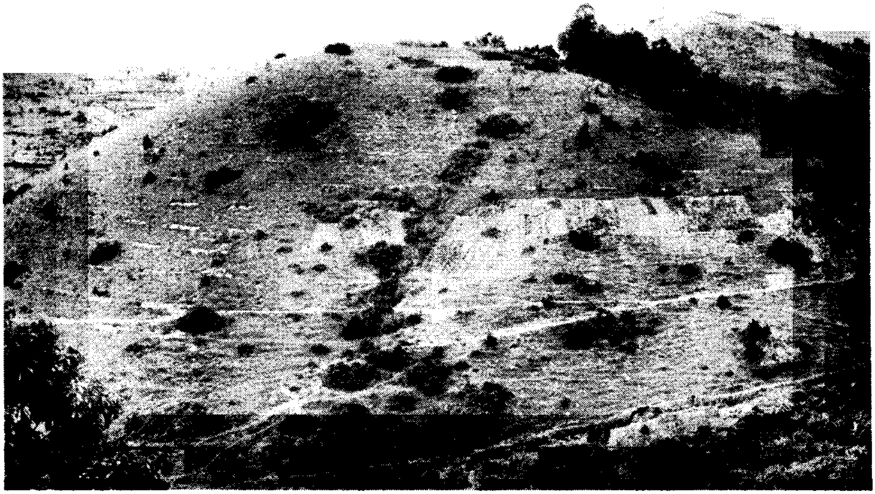
Awareness of the need for soil conservation arose in the United States of America (USA) in the 1930s. There had been many cases of irreversible soil loss by erosion before that time, perhaps as early as pre-classical times in the Mediterranean lands. Severe erosion occurred both in indigenous communities, 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. Butaré, 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 forestière 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 (Lal, 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 socioeconomic 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 × 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	Albic, Plinthic,
	Vertic Luvisols	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 (kg/m³)*
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					

B. 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
Cover crops	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 or buried	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 sepium*. 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 Lal, 1977; Abujamin, 1985). In western Nigeria, maize was found to reduce erosion by more

6. The cover approach: prunings of *Gliricidia sepium*, 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 as 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 undesirable and impracticable to attempt to change this situation. Ways must be found of permitting food-crop production to continue on sloping land.

In Asia, this problem has been commonly solved by terracing, as for example in North Yemen, Java, the Philippines and the Himalayan foothills of 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 decline may still present a problem). However, this solution requires a large amount of labour, spread over many years to build one extra terrace per year, and it is unlikely that it can be introduced to regions where it is not already customary.

Land evaluation

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

$$PI = \sum_{i}^{n} (A_i \times C_i \times D_i \times WF_i)$$

where A_i is an index of available water capacity in soil layer i, C_i similarly for bulk density, and D_i 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 cm normally 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 Lal 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).*

	Crop yield (kg/ha)		
	Very serious erosion	Less serious erosion	No erosion
Rough rice	484	715	659
Shelled maize	196	284	103[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]Based 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; Böjö, 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:cost 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.

Reduction 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 are 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.

Available 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.

Table 9. *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 (Lal, 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

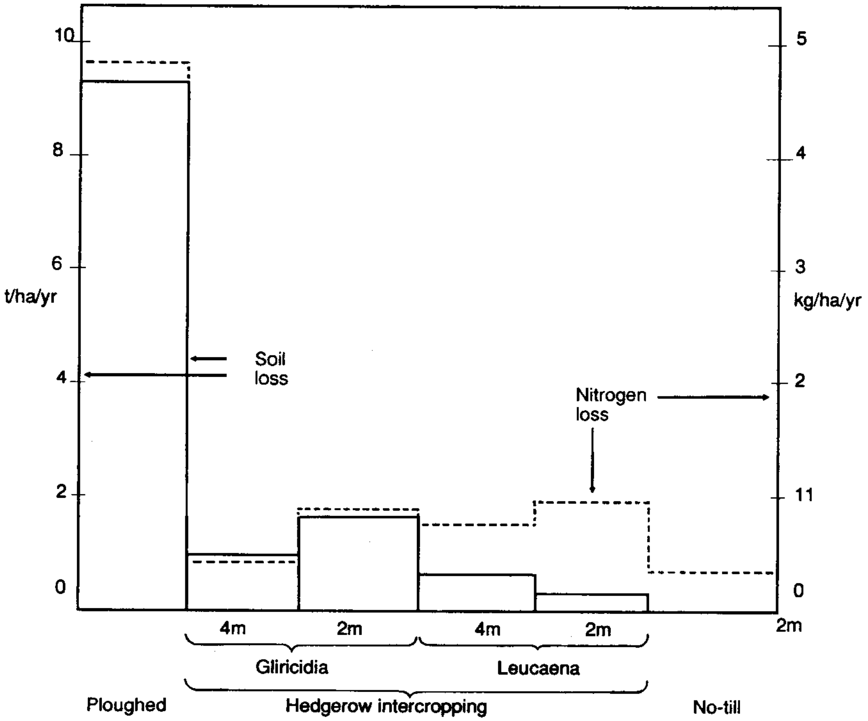


Figure 1. Losses of soil and nitrogen through erosion over two years under hedgerow intercropping, Ibadan, Nigeria (after data in Lal, in press).

(on both 45 and 75% slopes) by hedgerows of *Gliricidia sepium* (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, are 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.

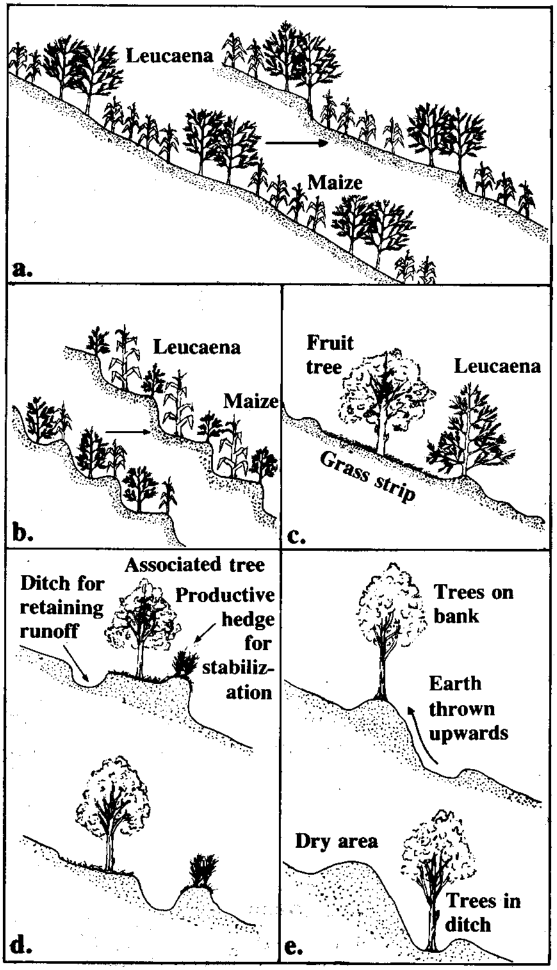


Figure 2. Examples of agroforestry in erosion control (1).

a. Barrier hedges of double rows of *Leucaena* with maize developing naturally into terraces, Philippines (after Celestino, 1985; Pacardo, 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 ICRAF Machakos field station).

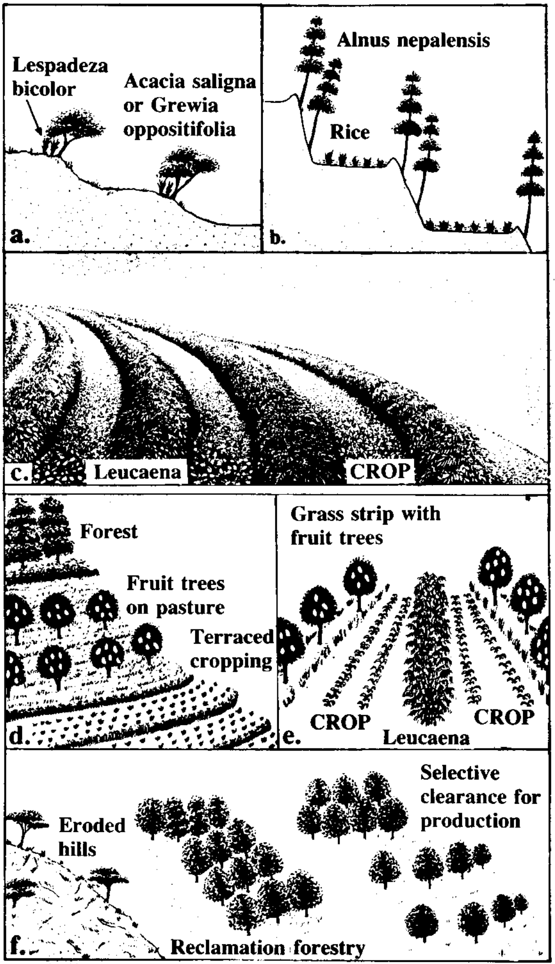


Figure 3. Examples of agroforestry in erosion control (2).

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 al., 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 Illuppallama, Sri Lanka.

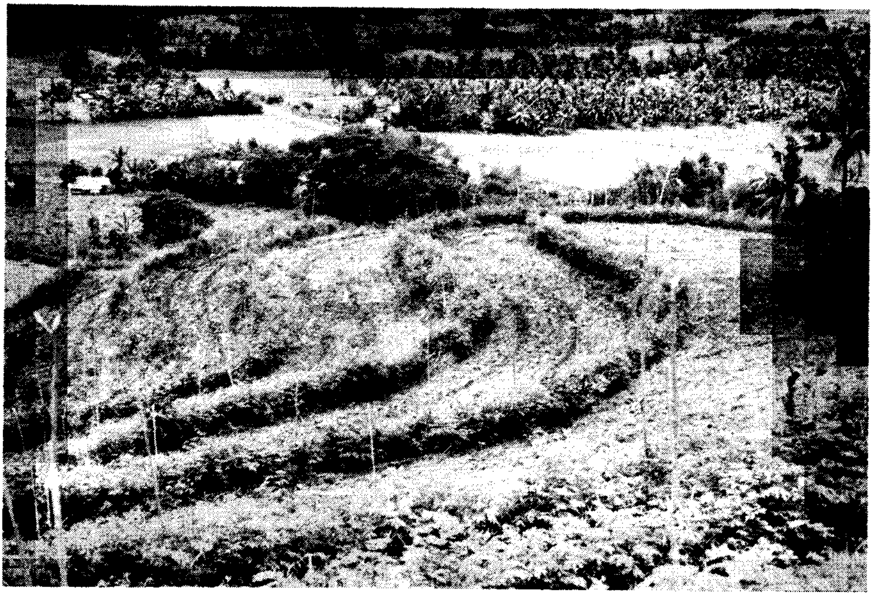
9. Supplementary use of trees in erosion control: *Grevillea robusta* on the bank of a ditch-and-bank structure. Butaré, Rwanda.

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, Erythrina* 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 siamea* 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, very 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 prunings: 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 für 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, are 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.

Examples 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 *Alnus 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	Any	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 III. 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.

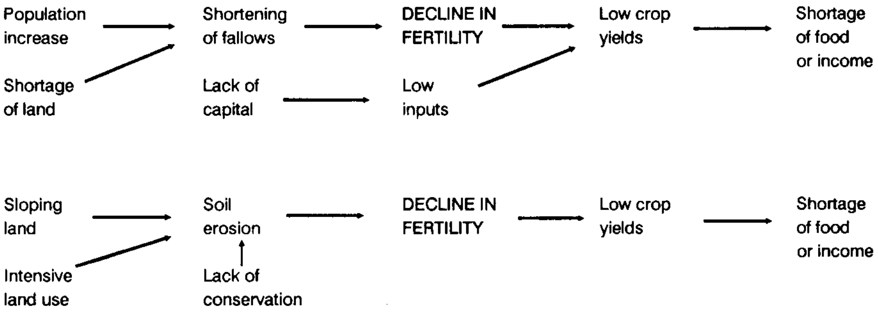


Figure 4. Chains of cause and effect linked to decline in soil fertility.

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, 1960; 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 Inputs		
Soil type (FAO)	Rain forest zone 270-365	Savanna zone 120-269	Semi-arid zone 75-119	Rain forest zone 270-365	Savanna zone 120-269	Semi-arid zone 75-119	Rain forest zone 270-365	Savanna zone 120-269	Semi-arid zone 75-119
Regosols and Arenosols	10	15	20	30	35	45	50	65	50
Ferralsols	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						
Vertisols	40	55	45	70	75	75	90	90	90
Fluvisols and Gleysols	60	70	90	80	80	90	90	90	90

These data conflict with the fact that at present the predominant form of rainfed 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.

Agroforestry 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 are 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 are 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).

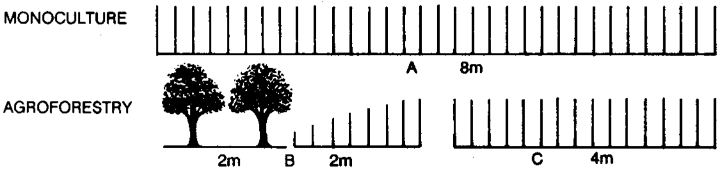
Extent of land. A constraint of extent of land was noted to apply to fallowing and green manuring, meaning that these practices required land over and above that needed for productive purposes. In the context of agroforestry, there are two critical questions:

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		CASE 2		CASE 3	
	Yield per m	Production	Yield per m	Production	Yield per m	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						
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 levels (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/100 g)	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_3—N	195	62
PO_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.

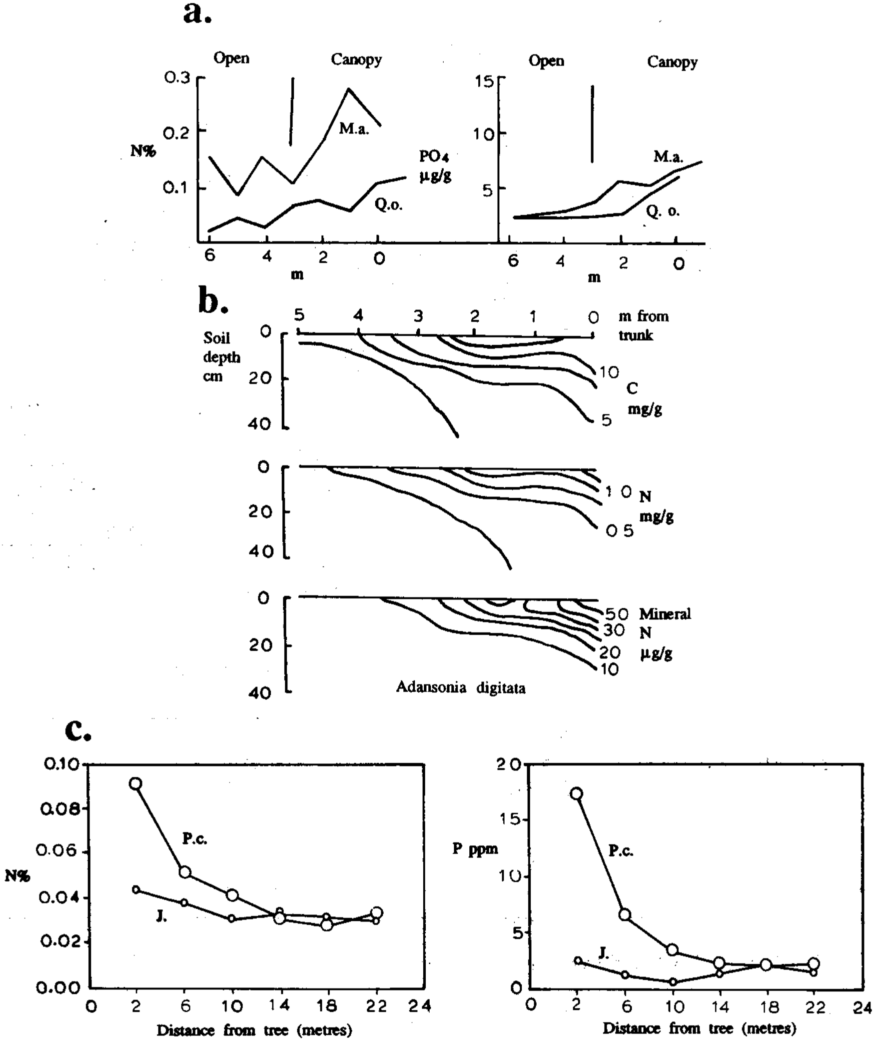


Figure 6. Tree-soil transects. A. Savanna, Belize, topsoil. M.a. = *Miconia albicans*, Q.o. = *Quercus oleoides* (after Kellman, 1980). B. Semi-arid grassland, Senegal (after Bernhard-Reversat, 1982). C. Tlaxcala, Mexico. P.c. = *Prunus capuli*, J. = *Juniperus* spp. (after Altieri et al., 1986).

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 *Prunus 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.

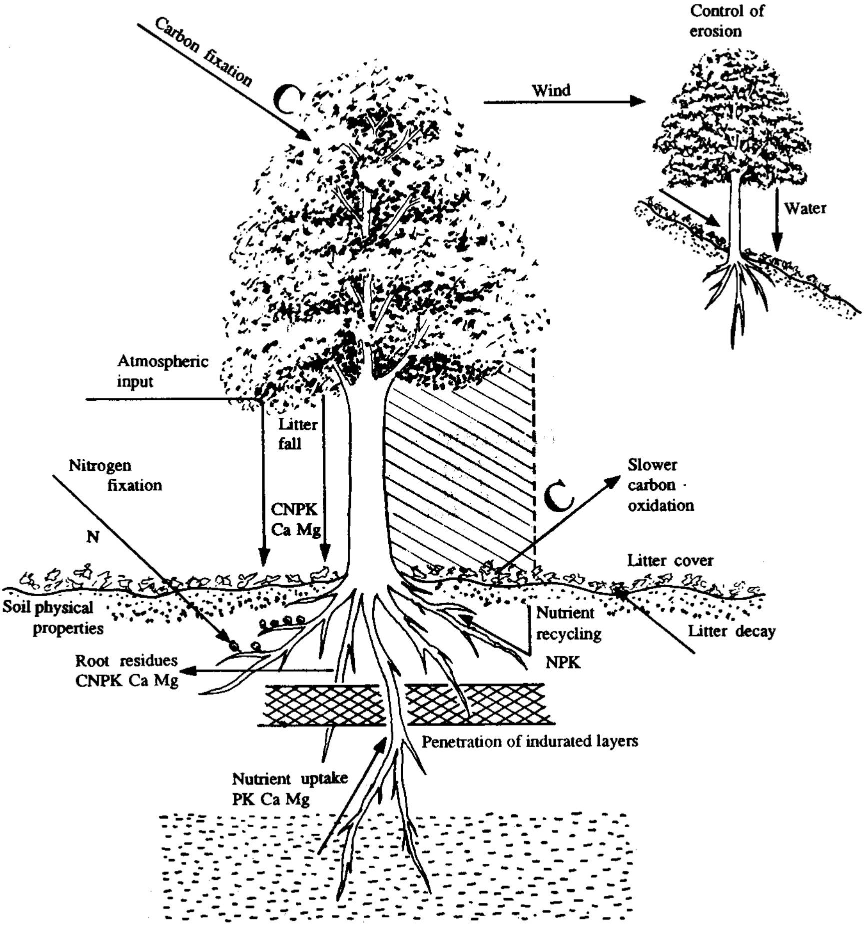


Figure 7. Processes by which trees improve soils.

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 μm in diameter determine available water-holding capacity, whilst those over 250 μm are necessary for root penetration. There is much evidence of the influence of physical properties of tropical soils on crop growth, independent of nutrient or other effects (Lal and Greenland, 1979).

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 50°C, that are experienced on bare soils in the tropics; and that high temperatures adversely affect crop growth (Harrison-Murray and Lal, 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 are 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 fine, 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:

$$C_1 = C_0 - KC_0$$

$$\text{or } C_1 = C_0 (1 - K)$$

where C_0 = initial soil humus carbon, C_1 = 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 & Fauck (1970)
woodland		Kc = 0.02–0.05	
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 subhumid		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	Dalal (1982)
South Australia	0.7		Ladd & Amato (1985)
Thailand		K = 0.077–0.088	Kyuma et al. (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:

$$C_t = C_o.e^{-rt}$$

where C_t = 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:

$$C_t = C_1 \cdot e^{-r_1 t} + C_2 \cdot e^{-r_2 t}$$

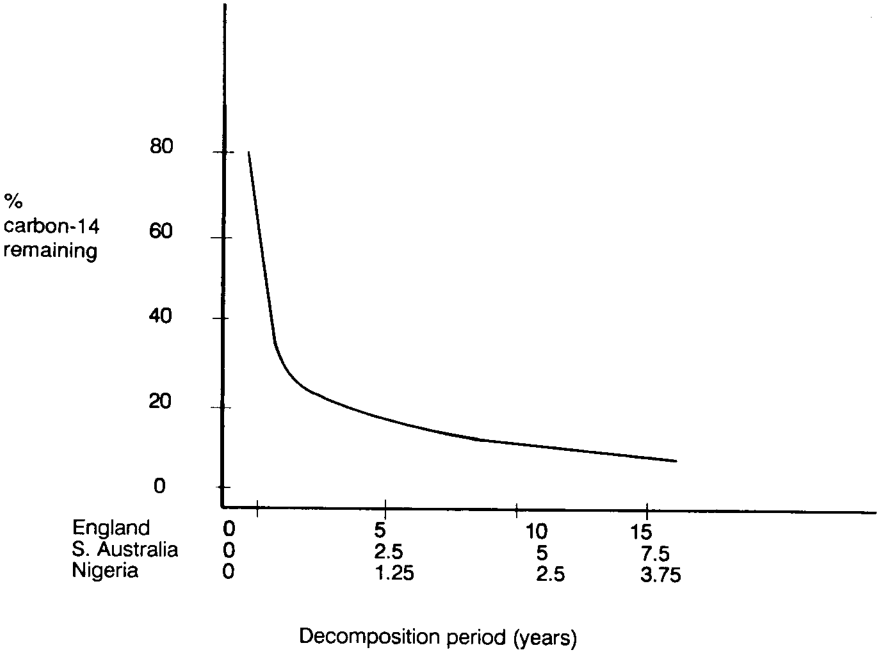


Figure 8. Decay curves for loss of carbon-14 labelled plant residues added to soil (after Ladd and Amato, 1985).

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) Parton et al. (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 (1960); 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

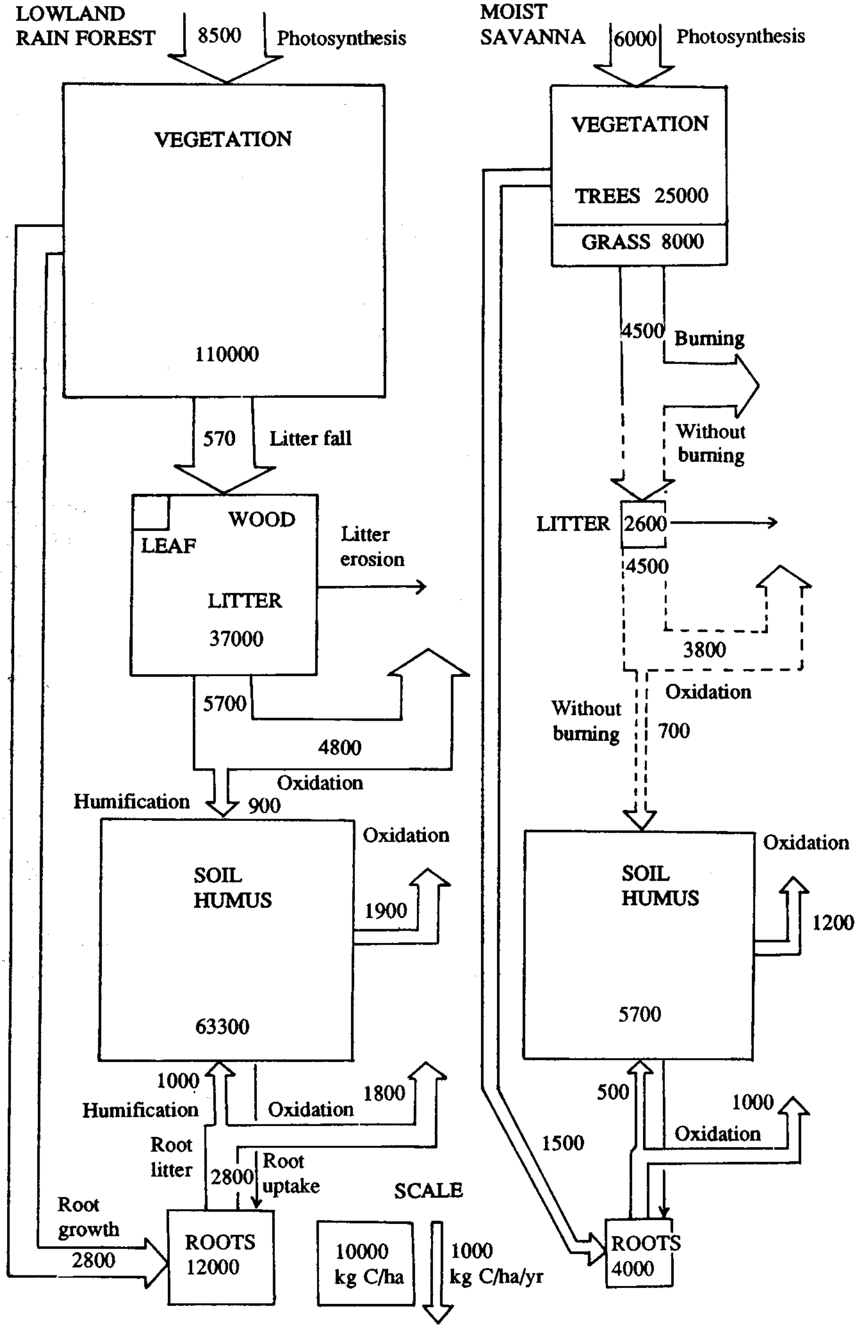


Figure 9. The carbon cycle under natural vegetation (after Young, 1976, p. 111, based mainly on data in Nye and Greenland, 1960).

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

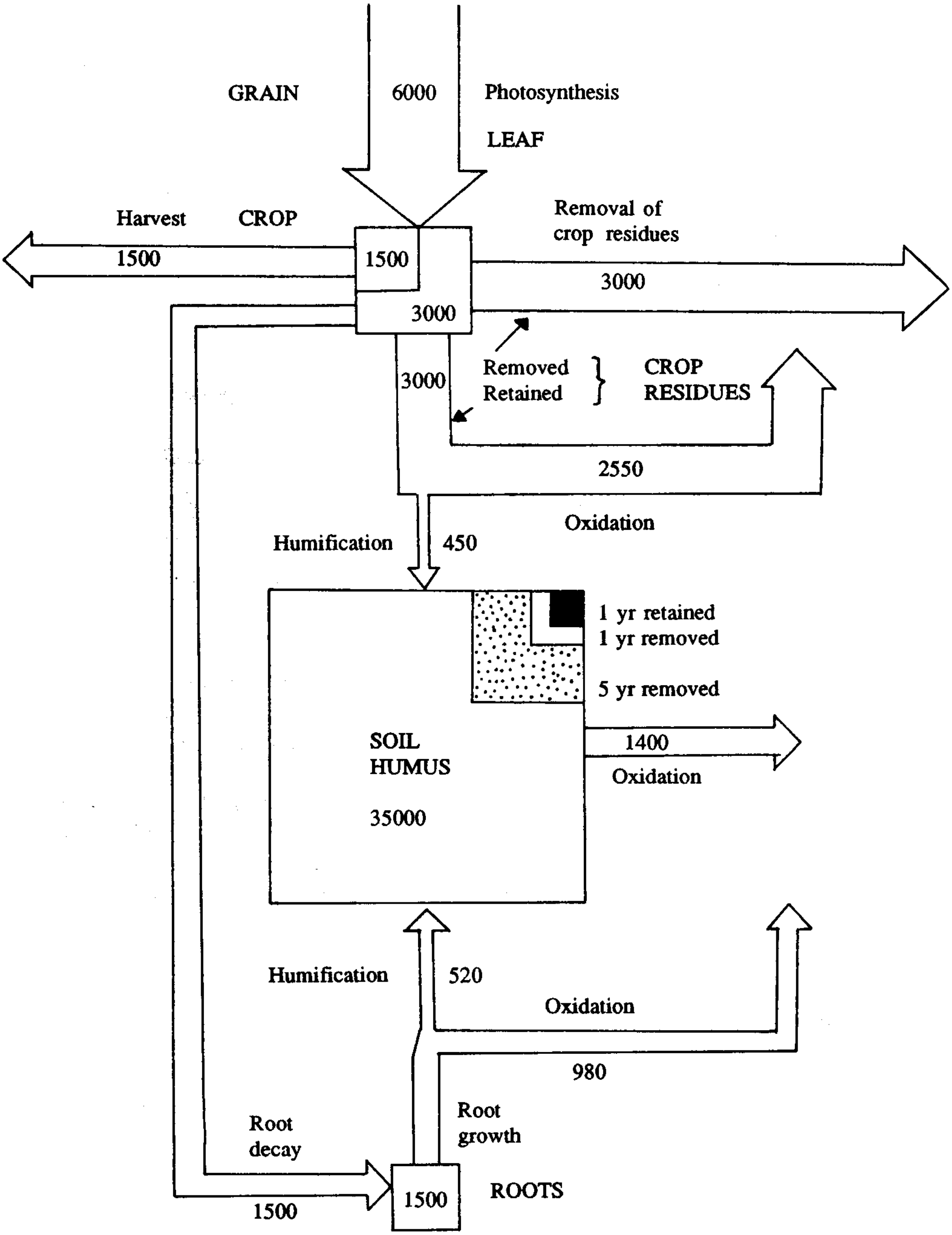


Figure 10. The carbon cycle under a cereal crop, lowland humid zone, crop yield 3000 kg/ha. Values are kg C/ha and kg C/ha/yr. Shaded areas show net losses of soil carbon.

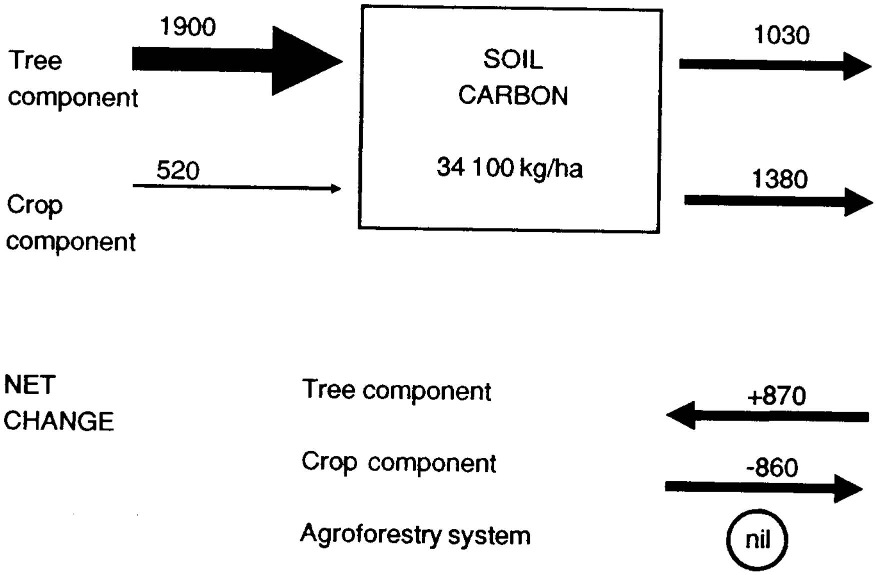


Figure 11. Changes in soil carbon under agroforestry. Data and assumptions are the same as for Figures 9 and 10.

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 (kg/ha/yr). The sources are reviews, with substantial communality in primary data sources.*

Vegetation community	Equivalent climate (Köppen)	NPP (kgDM/ha/yr) Range	Mean or typical	Source
Evergreen rain forest	Af	10 000–35 000	28 000	Leith (1976)
			23 000	Leith & Whittaker (1975)
			23 000	Murphy (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 & Whittaker (1975)
		13 000–17 000		UNESCO (1978)
			21 000	Murphy (1975)
Montane ('cloud') rain forest	Cf,Cm		22 000	Leith & Whittaker (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 Basilevič (1968)
Dry savanna	Aw	3000–8000	5000	Murphy (1975)
			7000	Rodin and Basilevič (1968)
Semi-desert vegetation	BS	100–2500	700	Leith (1976)
			2000	Rodin and Basilevič (1968)

dry season, is only slightly lower than evergreen forest in typical value, but does 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 (kgDM/ha/yr).

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 et al. (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	Alpizar et (1986, 1988)
		C. alliodora + cacao	16 360	
		Erythrina poeppigiana	8710	
		E. poeppigiana + cacao	15 740	
Philippines	Plantation	*Gmelina arborea*	12 700	Kawahara et al. (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	Kang et al. (1985)

Table 20 (cont)

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	Brewbaker (1987)
Dry subhumid				
India	Plantation	*Prosopis juliflora*	30 000	Gurumurti et al. (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	Felker et al. (1983)
Various				
Nigeria/Brazil	Plantation	*Gmelina arborea*	9300–24 900	Chijoke (1980)

The *Cordia*/*Erythrina* 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 (kgDM/ha/yr).

Climate, Country	Land use	Tree	NPP	Source
Humid				
Malaysia	Plantation	*Acacia mangium*	3060	Lim (1985)
Philippines	Plantation	*Albizia falcataria*	180	Kawahara et al. (1981)
Costa Rica	Hedgerow intercropping	*Calliandra calothyrsus*	2760	Baggio & Heuveldorp (1984)
Philippines	Plantation	*Gmelina arborea*	140	Kawahara et al. (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 et al. (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 (kg DM/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.