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CONSEJO INTERNACIONAL PARA INVESTIGACION EN AGROSILVICULTURA

P.O. Box 30677, Nairobi, Kenya, Tel: 29867. Telex: 22048 Cable: ICRAF

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42

THE POTENTIAL OF AGROFORESTRY FOR SOIL CONSERVATION

PART I. EROSION CONTROL

Anthony Young

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PREFACE

The present text of this review, as three working papers, is intended as a draft version prior to subsequent publication in book form. Work of significance has no doubt been omitted. Readers are earnestly invited to comment on matters of fact or emphasis, and to give details of relevant publications, reports and work in progress.

Anthony Young
Nairobi, November 1986

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THE POTENTIAL OF AGROFORESTRY FOR SOIL CONSERVATION

PART I. EROSION CONTROL

ABSTRACT

Soil conservation in its broader sense covers erosion control, the maintenance of soil fertility, and thus sustainable land use. This Working Paper, which forms Part I of the review as a whole, covers agroforestry in erosion control. Trends in soil conservation research and policy are reviewed, and assessed with respect to their significance for agroforestry. Attention is given to predictive models, the importance of soil cover, land evaluation, effects of erosion on land productivity, and economic and policy aspects. The impact of agroforestry on erosion is reviewed with respect to effects of trees on the causative factors of erosion, and examples of agroforestry practices in erosion control. The different lines of evidence are summarized in terms of the probable effectiveness of specified agroforestry practices as a means of erosion control. The combination of a high apparent potential with sparse data means that there is a clear need for research. The objectives and design of research are discussed. The conclusions from the review are given in the Summary which follows.

SUMMARY

The main conclusions from this review are as follows (numbers in brackets refer to sections of the text):

1. There are two main aspects of soil conservation: erosion control and maintenance of fertility. These are closely inter-related. Both are necessary in order to achieve sustainable land use (1.1).

2. The earlier approach to soil conservation centred upon rates of soil loss. The requirements of arable cropping were taken as fixed, and hence conservation measures were directed at reducing runoff, through earth structures. On the basis of assessed land capability, much sloping land was regarded as only suitable for non-arable use. In extension, soil conservation was often treated in isolation, and sometimes on the basis of quasi-legal compulsion (2.2.1).

3. Arising from problems in the earlier approach, and recent research, greater attention is now given to the effects of erosion on soil properties and crop yields. In conservation, there is greater emphasis on maintaining a soil cover, as compared with checking runoff. Where sloping land is already under arable use, means must be found of making this sustainable and acceptable. In extension, it is recognized that conservation is only likely to succeed where it is implemented through the willing cooperation of farmers. It must therefore be in their perceived interests, as an integral part of improvements leading to higher production (2.2.2).

4. Aspects of these recent trends significant to agroforestry are:

   - the potential of agroforestry for fertility maintenance should be considered jointly with that for erosion control;

   - particular attention should be given to the capacity of tree litter to maintain soil cover;

   - it is important to develop agroforestry systems with the potential for sustainable land use on sloping lands;

   - soil conservation should be an integral part of the process of diagnosis and design (2.2.3).

5. The leading models for prediction of erosion are all based on the same controlling variables: rainfall erosivity, soil erodibility, slope (angle and length), and soil cover. A review of these models demonstrates the primary importance of the soil cover factor. In general terms, there are greater opportunities to reduce erosion through maintaining a soil cover than by means of the runoff barrier approach (2.3).

6. Experimental evidence supports that of models in showing the high potential for erosion control of soil cover. However, the effect of tree canopy cover is relatively small (and may even be negative). Ground litter or mulch, on the other hand, is highly effective; a litter cover of 60% will frequently reduce erosion to low levels, even without additional measures of the barrier type. The main potential of agroforestry for erosion control therefore lies in its capacity to maintain a ground surface cover of tree litter (2.5).

7. In assessing the relative capacity of agroforestry for helping to solve land use problems in different environments, among those for which its potential is highest is in areas of sloping lands (2.6).

8. Soil erosion is the cause of substantial lowering of crop yields and loss of production. The effect on yields is in general greater on tropical than on temperate soils, and greatest on highly-weathered tropical soils. The major causes of such yield reduction are loss of organic matter and nutrients and, in dry areas, loss of runoff and lowering of available water capacity. Hence, agroforestry practices which combine maintenance of fertility with control of soil loss are of particular importance (2.7.1).

9. Where erosion is treated as simple loss of soil depth, it is frequently difficult to justify conservation in economic terms. Economic justification is frequently possible, however, on the basis of prevention of crop yield losses. Agroforestry methods usually have lower initial costs than terracing or bunds, and also have the potential for maintaining or increasing crop yields. It is therefore likely, other things being equal, that conservation by means of agroforestry will show more favourable results from economic analysis than conservation by means of physical earthworks (2.7.2).

10. Soil conservation by means of an enforced policy frequently does not work. Conservation is likely to be most effective where it is conducted with the active cooperation of farmers, in their perceived interests, and integrated with other measures for agricultural improvement. This situation is in good accord with the diagnosis and design approach to the planning of agroforestry (2.8).

11. On the basis of the limited available evidence, the effects of agroforestry on the causative factors of erosion appear to be as follows:

    - rainfall erosivity is often reduced only slightly (by the order of 10%), and may sometimes be increased, by the presence of a tree canopy;

    - the resistance of the soil to erosion, which commonly decreases under continuous arable use, can be sustained through the capacity of agroforestry to maintain soil organic matter;

- reduction of runoff is possible under several agroforestry practices, in some cases in conjunction with barrier earthworks;

- the major potential effect of agroforestry, however, is likely to be through the capacity to establish and maintain a ground surface cover of litter during the period of erosive rains (3.2.2).

12. Data on recorded erosion rates under agroforestry are sparse. The presence of trees does not necessarily lead to low rates of erosion. What matters is the spatial arrangement of the trees and, especially, the way in which they are managed (3.2.3).

13. In the design of agroforestry systems for erosion control, the primary aim should be to establish and maintain a ground surface cover of plant litter. This conclusion is supported by a range of convergent evidence, direct and inferential (3.2.4).

14. Viable methods of erosion control through agroforestry have been designed, recommended or are being tried in more than 10 countries, in some cases on the basis of experimental results, at other sites on an empirical or trial basis (3.3).

15. Firm knowledge of the effects of agroforestry practices on erosion is sparse. On the basis of such data as exist, the probable effects may be summarized as follows:

Barrier hedges. This practice can control erosion, through the combined effects of checking runoff, providing a soil litter cover, maintaining soil organic matter, and through progressive transformation into terraces (3.4.2).

Trees on soil conservation works. Where earth structures are established, the planting of trees on them can make productive use of the land occupied, help to stabilize the structures, in some cases add to their protective effects, and fulfill a psychological function of making it more likely that the structures will be perceived as beneficial, and maintained. This applies to trees on bunds and related contoured earth structures, grass barrier strips, and terraces (3.4.3).

Alley cropping. There is substantial inferential evidence that alley cropping, with the tree rows set out along contours, has the potential of providing a litter cover on the cropped alleys and a barrier function through the tree rows. Effective erosion control will not be automatic, and will vary with detailed design and management practices. Given the apparently high potential coupled with the sparsity of experimental data, there is an urgent need for controlled measurements of erosion rates under alley cropping (3.4.4, 4.2).

Plantation crop combinations, multistorey tree gardens and home gardens. These practices, in which there is a dense, regular or random tree cover, have the potential for erosion control. In

the case of multistorey gardens, such control is intrinsic to the nature of the practice. For plantation crop combinations, control depends on management, specifically the maintenance of a ground cover of litter (3.4.5).

Sylvopastoral practices. Erosion control on grazing land depends primarily on the basic, established practices of pasture management, notably limitation of livestock numbers and rotation of grazing. Sylvopastoral methods alone are unlikely to succeed, but can contribute when carried out in conjunction with other measures for pasture management. A specific potential is for reducing grazing pressure through provision of protein-rich fodder at those times of the year when grass pasture is scarce (3.4.6).

Planted tree fallow and taungya. Planted tree fallow can check erosion during the period of fallow, but erosion control as a whole will depend mainly on practices during the cropping period. For taungya, limited evidence suggests there may be some increase in erosion during the cropping period, as compared with pure tree plantations, but probably not a substantial adverse effect (3.4.7).

16. The objectives of research into erosion control through agroforestry should be: (i) to confirm the effectiveness of erosion control by specific agroforestry practices in given environmental conditions; (ii) to build up knowledge of the processes by which this is achieved, and thereby assist in the efficient design of effective systems; (iii) to reconcile systems that are optimal for erosion control with other design requirements; (iv) to test the response of farmers to erosion control through agroforestry; and (v) to evaluate the overall effectiveness of agroforestry systems on land with an erosion problem.

These objectives require a combination of on-station research, on-farm trials and broadly-based studies. Much of the research will be specific to particular environments (4.1).

17. There is a large and growing problem of erosion, a considerable apparent potential for its control by means of agroforestry, and a paucity of data to confirm this hypothesis. This combination of circumstances clearly and strongly indicates the need for research (4.3).

1 INTRODUCTION

1.1 Erosion control, the maintenance of soil fertility and sustainable land use

This text forms part of a review of the role of agroforestry in soil and water conservation. In the review as a whole, soil conservation is interpreted in its wider sense, to include the maintenance of soil fertility as well as the control of erosion.

It is commonly said that there are three desirable properties of land use systems: productivity, sustainability and practicability. Productivity means that the system should be capable of producing the goods required by the farmers, whether for subsistence or cash production; practicability that it should be a system which farmers can adopt, within the constraints imposed by the farmers' own capital and labour availability and the inputs and services locally available. Sustainability refers to whether the system can remain productive for a long period; this depends for the most part on whether it conserves the natural resources on which production is dependent.

Viewed in this broader sense, soil and water conservation covers the following aspects:

i) erosion control - water erosion
- wind erosion;

ii) maintenance of soil fertility;

iii) water conservation.

Of these aspects, the control of wind erosion and water conservation are both of particular significance in semi-arid regions, and are not covered in the present text. An interim review has been given in Depommier (1985) and it is intended that this shall be treated further in two forthcoming publications in the agroforestry review series: Agroforestry for soil and water conservation in dryland Africa, and Shelterbelts for agroforestry.

1.2 Previous reviews

Most accounts of agroforestry mention or emphasize sustainability as one of the beneficial properties of land use systems based upon it. Reviews which are specifically about soil conservation are few in number:

- Four papers in the symposium, "Soils research in agroforestry" (Mongi and Huxley, 1979) are concerned with maintenance of soil fertility under agroforestry, those by Ahn, Okigbo and Lal, Sanchez, and Tejwani. That by Pereira reviews experience of watershed experiments on water yield and soil conservation under forest plantations as compared with other land use systems. Like many discussions of agroforestry (including part of the present one), these papers are largely based on taking experience from related kinds of land use and assessing its significance for agroforestry.

- Nair (1984). This is the major review to date of soil fertility maintenance and soil productivity under agroforestry systems. Whilst directed primarily at productivity, it refers to conservation as an integral aspect. The treatment is basically to take the main existing agroforestry systems, both traditional and modern, and assess knowledge of soil productivity and sustainability under each.

- Wiersum (1984). This is a comprehensive review of measured rates of water erosion under agroforestry systems. It is of outstanding value for its synthesis of evidence drawn from diverse sources, some difficult of access.

- Lundgren and Nair (1985). A review which sets out the interdependence of erosion control and fertility maintenance, and outlines the capacity of agroforestry systems to combine these with productivity.

- Depommier (1985). An account of the role of woody plants in conservation and rehabilitation, with emphasis on windbreaks and live fences. It is of particular value for its summary of evidence from francophone Africa.

The above accounts are freely drawn upon in the present review.

1.3 Arrangement of the text

1.3.1 The review as a whole

It is a basic argument of this review that erosion control and fertility maintenance are interdependent. Erosion leads to a reduction in fertility, whilst the physical, chemical and biological soil degradation commonly referred to as 'decline in fertility' has among its effects a reduction in the soil's resistance to erosion.

For purposes of analysis these aspects, erosion control and maintenance of fertility, are first treated separately. Integration is achieved by including within the discussion of erosion control an account of the effects of erosion on fertility; and conversely, in the discussion of fertility maintenance, by taking erosion into account as a factor contributing to fertility decline. Both aspects are then combined in the form of a computerized model, for prediction of soil changes under agroforestry systems.

In the present draft version, erosion control, fertility maintenance, and the combined model are published as three working papers, of which this is the first. In the final version, these will become sections of a single publication.

1.3.2 The review of erosion control

Evidence from direct experimental observations on erosion under agroforestry systems is relatively 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.

The discussion in this working paper is therefore divided into two parts. The first 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. The second part consists of a review of agroforestry practices in relation to soil conservation, using both direct evidence and hypothesis of likely effects based on the preceding review. These are followed by a summary and conclusions.

2 TRENDS IN SOIL CONSERVATION RESEARCH AND POLICY, AND THEIR SIGNIFICANCE FOR AGROFORESTRY

2.1 General

2.1.1 Awareness of the need for soil conservation

Awareness of the need for soil conservation arose in the US 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, for Homer writes words to the effect, "Do not believe that the barren hills have always been as you see them. Once they were forested and fertile"! 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 40s. 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), Lord 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 Southern Rhodesia (Zimbabwe), where conservation practices imported and adapted from those of the US were widely applied.

Whilst soil conservation specialists never wavered in their advocacy, awareness and policy emphasis among governments became less 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 ten years and is still growing. Looking to the future, a recent review of factors affecting land resources and their use over the next 50 years lays much stress on the need to control soil degradation (Young et al., in press).

2.1.2 Recent studies of erosion and conservation

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 in general, with emphasis on measurement of rates.

- Kirkby and Morgan (1981). Not a symposium but a multi-author 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). The most comprehensive recent 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 the examples described drawn particularly from the Philippines and Asia.

- Follett and Stewart (1985). A symposium on soil erosion and crop productivity.

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

2.2 Trends in research and policy

2.2.1 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 (1971) is a clear summary with a focus on the topics 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 (1979), Leblond and Guerlin (1983), Weber and Hoskins (1983a), together with many national handbooks, for example those for Kenya (Wenner, 1981) and India (Singh, Ventakataramanan and Sastry, 1981).

The following is a summary of features of the traditional approach. Whilst it may be selective, to point 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 the reduction of soil loss to a presumed acceptable limit, termed "tolerable erosion".

   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 US (Klingebiel and Montgomery, 1961) and was adapted for many tropical countries, e.g. Malawi (Shaxson et al., 1977), 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 notable successes were achieved through implementation of this approach. 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; in some cases, the rates of what was "tolerable" were simply raised to accord with those realistically achievable, without scientific justification for doing so (cf. points 2a and 2b above).

- 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 unacceptable (cf. 3).

- 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 this should not be done. A way had to be found to make such cultivation environmentally acceptable (cf. 4).

- 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 benefit occurs (cf. 5 and 6).

- 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 (cf. 2c).

2.2.2 Recent trends

Changes to the earlier policy have come about through advances both in natural and social science. These recent trends, as set out in the symposium volumes noted above, 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 effects of erosion are by no means limited to loss of soil depth, but affect also water-holding capacity, nutrients, organic matter and, through the latter, soil physical properties (papers in Greenland and Lal, 1977, and 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 the latter 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 now 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 yields (e.g. Queblatin, 1985).

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).

2.2.3. Implications for agroforestry

Taking the above itemized trends in turn, 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 (cf. points 1 and 2a above).

- Agroforestry has a potential through the soil cover provided by tree canopy and litter, in addition to the role of trees in relation to the runoff barrier function (cf. 3). This is an aspect of much significance, discussed further 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.

- In drier regions, erosion control should also be assessed jointly with the role of trees in water management (cf. 5).

2.3 Predictive models and their significance

2.3.1 Introduction

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. Erosion models have been reviewed by Rose (1985a).

The USLE is based on a vast amount of experimental data for the US (15000 "plot-years"), and has been calibrated and validated to a much more limited extent for some tropical areas. The SLEMSA model is based on data from tropical and subtropical sites. Both these models can be taken as reasonably correct summaries of the causes of erosion, insofar as they indicate the relative effect on erosion rates of different contributory factors. The FAO model is essentially a simplification of the USLE.

The purpose of the present review is to show, by an examination of the nature of these predictive models, what is the relative importance of different factors contributing to rates of erosion; and thereby, to indicate aspects of potential significance for the planning of soil conservation based on agroforestry.

2.3.2 Features of the models

The universal soil loss equation (USLE) (Wischmeier and Smith, 1978; for discussion, see Wischmeier, 1976). This 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) for farmland under similar treatments, to a level of accuracy sufficient for land use planning purposes. It is designed to predict erosion for a specific site, such as a field. All the original work was carried out in non-metric units, but it has been converted to a metric basis.

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

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

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. This value is also called the EI_{30} index, and is dimensionless. 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, Babu and Chandra, 1981; 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 400.

K, the soil erodibility factor, describes the resistance of the soil to erosion. It is also dimensionless. K is set such that the product (R x K) gives the soil loss rate on bare soil on a standard erosion plot, in tonnes per hectare. A standard plot is 22 m long with a uniform 9% (5.14°) slope. (In using data, it is essential to make sure that the

values of the R and K factors are compatible; namely, either both metric and giving erosion as tonnes per hectare, or both non-metric and giving erosion as short tons per acre.)

Although K = 0 for a hypothetical totally-resistant soil, there is no specific meaning for K = 1. 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 luvisols) 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, or LS, factor, read from a table or graph.

C is the cover and management 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. By definition, C cannot exceed 1.0 (the value for bare fallow itself) nor fall below zero (complete cover at all times of the year); in practice, it varies over almost the full range of these extremes.

For example, an annual crop with low soil cover, such as a low-yielding crop of 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.

<u>The soil loss estimator for southern Africa (SLEMSA)</u> (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 has the advantage of being designed and calibrated specifically for southern Africa.

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; any 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. Of importance is the fact that the SLEMSA model was independently derived and calibrated from experimental data drawn from a tropical to subtropical region.

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 assessment of 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 prediction of 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 of value 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 texture classes of the FAO-Unesco Soil Map of the World (FAO/Unesco, 1970-80);
- 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, 1985b; Rose and Freebairn, 1985) 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 one feature, namely the treatment of the relation between soil cover and sediment entrainment.

Cover is represented as C_r, the fraction of soil surface exposed, and sediment entrainment efficiency by a non-dimensional factor n. At $C_r = 0$ (bare soil), $n = 0.7$, whereas at $C_r = 0.9$, 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, C_r	Sediment concentration, kg/m³
1.0 (bare soil)	190
0.9	55
0.5	8
0.3	4
0.0 (100% co[illegible])	1

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

2.3.3 Implications of the models

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 varibale 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 length is altered by the conservation practices that operate by checking downslope runoff: barrier strips (grass or trees with grass), bunds, barrier hedges, storm drains and cutoff ditches. Barrier strips and hedges are relatively cheap forms of conservation, bunds and ditches in the middle of the cost range (in terms of labour or capital). As effective slope length is reduced, rate of erosion decreases approximately linearly but less than proportionally, i.e. halving the slope length reduces the erosion rate by less than half. On relatively gentle slopes, up to about 15% (8.5°), barrier-type conservation works can effectively control erosion. 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 barrier is narrow.

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

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 these values. Typical values, taken from those established for West Africa by Roose (1977) are:

Maize, sorghum, millet (depending on yield)	0.9-0.4
Cassava, yams (depending on planting date)	0.8-0.2
Oil palm, rubber, coffee, cocoa with cover crops	0.3-0.1
Banana: - residues burnt	0.5-0.1
- residues left on surface	0.01
Fast-growing cover crops	0.1-0.01
Overgrazed or burnt savanna	0.1
Savanna in good condition	0.01
Dense forest	0.001

There are many points of significance in these values. First, an annual crop alone is likely to reduce erosion to something of the order of half that on bare soil. Reduction will be less if it is low-yielding or late-planted. A high-yielding and well-managed cereal crop will only lower it by a factor of 0.4, that is, reduce the 255 t of the above example to 100 t. But perennial tree crops with cover crops beneath, or well-managed cover crops alone, can reduce erosion to between 0.1 and 0.01 of its rate on bare soil. The differences between bananas with and without residues left on the surface, and between savanna in good and in poor condition, further point to the large influence of land cover.

In summary, the combined effects of rainfall, soil erodibility and slope will frequently lead to rates of erosion which are certainly unacceptable, whilst cereal and root crops do not [illegible]tly 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. This conclusion obtained from predictive models is supported by experimental evidence reviewed in Section 2.5.

2.3.4 Significance for agroforestry

Two points of significance for agroforestry emerge from this review. First, if conservation by means of the barrier function is to be practicable on steep slopes, the barriers must effectively check soil and water flow, and at the same time must be narrow. The barrier hedge meets these requirements. So far developed with Leucaena*, it can be planted between contour-aligned rows of annual crops without changing the spacing of the latter at all.

Secondly, since soil cover has such large effects in controlling erosion, research in agroforestry, and its application in practical conservation, should give particular attention to the cover effects of trees and shrubs. These can operate through the tree canopy, but there is an obvious conflict with shading the crop. More important is the potential for covering the ground surface by tree leaf and branch

*Throughout this publication, Leucaena refers to Leucaena leucocephala.

litter, obtained from pruning the tree component. Thus pruning, carried out in the first instance to control shading, can have the added effects of both enhancing fertility and exercising a substantial control over erosion.

2.4 Acceptable rates of 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. Such limits will vary according to soil type. 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.

The concept of "tolerable erosion" or "soil loss tolerance" has, however, often been misleadingly used and should be clarified. 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 to 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. It should be noted that the original statement referred to formation of topsoil from already weathered soil material. The initial weathering of rock into fine particles is typically about 10 times slower, varying very widely with rock type and climate, although some subsequent discussions confuse these two processes (Smith and Stamey, 1965; Stocking, 1978; McCormack and Young, 1981; American Society of Agronomy, 1982; Saunders and Young, 1983; Young and Saunders, 1986).

The U.S. Soil Conservation Service sets limits for tolerable erosion, ranging mainly from 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: some two thirds of U.S. maize land experiences erosion rates of more than 11.2 t/ha/yr. Some tropical countries have adopted the upper limit, although it is frequently found to be impracticable to achieve it.

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 (Section 2.7.1). 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. This applies to agroforestry equally with other land use systems. 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.

2.5 The importance of soil cover

There is abundant experimental evidence to support the conclusion made above on the basis of predictive models, that soil loss can be greatly reduced by maintenance of a good land cover. This approach has been called in Rwanda, "agriculture de couverture du sol" (Dressler and Neumann, 1982).

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, 1971, pp. 204-5; 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 rate of growth both give more cover and increased protection (Hudson, 1971, pp. 199-200). 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).

A notable instance 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).

A ground cover of mulch is equally effective in controlling erosion. With straw or crop residue mulches of the order of 5 t/ha soil losses become small, whilst amounts of 1-2 t/ha can still have substantial effects (e.g. Lal, 1976, 1977a, 1977b, 1984; Okigbo and Lal, 1977; Abujamin, 1985). In western Nigeria, maize was found to reduce erosion by more than was predicted from canopy cover; it seems likely that the additional factor was crop residues on the surface (Wilkinson, 1975). 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). A mulch cover does not need to be complete; a spatial cover of 60% or over is effective.

A study of a 5-year-old Acacia auriculiformis plantation under a lowland humid climate in Java compared the effects of the tree canopy, undergrowth and litter, by artificially removing each combination of these layers. 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 <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 multi-layered plant structure may provide quite a dense canopy, but this is likely to be matched by the ground cover. In zoned practices, such as alley cropping, 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:

i. The greatest potential of agroforestry lies in its capacity to supply and maintain a ground cover.

ii. The direct effects of the tree canopy in providing cover are less than those of ground litter.

iii. 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 loss 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-decay species.

2.6 Erosion risk, land classification and land evaluation

2.6.1 Land capability classification

There are two main approaches in use for 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.

Land capability classification is the system which originated in the U.S., 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, 128-139; Shaxson et al., 1977, 148-158).

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 it was for soil conservation purposes that the system was primarily designed. 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.

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 the 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 as one extra terrace per year, and it is unlikely that it can be introduced to regions where it is not already customary.

2.6.2. 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 the rate of erosion which is acceptable, e.g. 10 t/ha/yr. Erosion under the specified use is estimated for each land unit, using one of the predictive models (Section 2.3). Where the predicted erosion exceeds the acceptable level, that area of land is rated as not suitable for the use. In assessing the acceptable erosion, what matters is not the rate of soil loss as such, but its effects on productivity (Section 2.4) (FAO, 1983, pp. 113-120; Bennema and de Meester, 1981).

This approach, 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 basic form of use in such a way that it may become suitable on land to which it was unsuited in its original form; this process of successive adaptation between land and land use is known as matching (FAO 1976, 1983, 1984; Dent and Young, 1981; Young, 1984).

2.6.3. Agroforestry and the use of sloping lands

The introduction of agroforestry practices may provide a solution to the dilemma between the existence of a high erosion hazard, under conventional arable farming, on sloping land, and the fact that large areas of such land are already under arable use and must remain so. Certain practices, including barrier hedges, alley cropping and multistorey tree gardens, have the potential to permit arable cropping on sloping land coupled with adequate soil conservation, leading to sustained productive use (Section 3.4). 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 would be neither desirable nor practicable to introduce an additional class of land use, "agroforestry", into land capability classification. 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, 1984, 1985a).

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 for these. 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 not 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, 1986).

2.7 Erosion, soil productivity and economics

2.7.1 Erosion and soil productivity

Only in recent years has sufficient attention been directed at 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 U.S., 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; American Society of Agricultural Engineers, 1985; Crosson, 1985; Follett and Stewart, 1985; Lal, 1985; Larson et al., 1985; Stocking and Peake, 1985, 1986; Williams, 1985; Yost et al., 1985; 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:

i. 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.

ii. Determine the productivity index for each soil type, in its present condition.

iii. 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 U.S. 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.

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 U.S., and it is to be hoped that it will be tested for tropical conditions (National Soil Erosion ...Committee, 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 high 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 0.2% 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 2-4, and occasionally as high as 10, being higher on gentle slopes and for moderate rapid as compared with very rapid erosion (Roose, 1977; Bhati, 1977). 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 thes factors is not known.

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

i. 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.

ii. 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 luvisols, the first 10 mm (c. 140 t/ha) of erosion will cause a reduction in yield of the order of 75%; for further erosion, the reduction is slower.

iii. Yield decline is greatest on "old", 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 ferralsol of the highly-weathered kind common on plateau sites in the subhumid zone (the "sandveld" soils of southern Africa or "cerrado soils" of South America). 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 <u>removing</u> two bags of fertilizer per hectare!

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 5 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 1). In all cases, yields are lower with very serious than with less serious erosion, 45-48% lower for the largest samples, the farmers reporting rice and maize yields.

Table 1. Average crop yields by degree of seriousness of erosion, as judged by farmers, Philippines (Librero, 1985).

Crop	Crop yield, kg/ha		
	Very serious erosion	Less serious erosion	No erosion
Rough rice	484	715	659
Shelled maize	196	284	103*
Bananas	544	1204	912
Cassava	(176)	2387	4140
Coconut (nuts/ha)	(270)	3858	4567
Coffee	(81)	82	(51)

( ) = based on sample of less than 5 farms.

*Explained by low planting densities

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 water capacity. This not only reduces average crop yields but also increases the risk of crop failure through drought.

Two conclusions emerge from this review, 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.

2.7.2 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 from 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.

On 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 discount rates. 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 analyzing 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). 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.

Nevertheless, 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.

Significant features intrinsic to agroforestry, or to be aimed at in the design of agroforestry systems in which soil conservation is an objective, are:

i. The initial cost, 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.

ii. 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.

Agroforestry can be applied to circumstances of erosion prevention, control and reclamation. In the case of reclamation of degraded land, the first step is to establish reclamation forestry, including

nitrogen-fixing species, without initially taking any harvest so as to allow all plant residues to reach the soil. As soon as a satisfactory check of erosion and build-up of soil humus have been achieved, techniques of agroforestry provide ways of combining continued erosion control with productive use. 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). For the reclamation of severely degraded hills in north Vietnam, a system advocated, but not tested, 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).

2.8 Conservation and extension policy

There has been a change in policy 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 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 more effective. 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).

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, 1985):

- 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;

- training of local extension services 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 farmer is consulted at the stage of diagnosis as to what is her 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 locally regarded 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 (alley cropping, 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 Science Council, 1983; Wijewardene and Waidyanatha, 1984; Douglas, 1984).

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 leuco 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 leuco does not grow well;

- soil conservation is linked to other farming concerns; for example, using napier grass together with leuco in hedgerows where this is attractive to farmers raising livestock.

3 AGROFORESTRY IN EROSION CONTROL

3.1 Introduction

This Section is concerned with the role of agroforestry practices in erosion control. Two kinds of evidence are available:

i. Experimental studies of erosion, including those made under indigenous agroforestry systems, experimental stations, and relevant information from other land use systems which include tree cover.

ii. Examples of the use of agroforestry practices in erosion control.

These two sets of data are covered in Sections 3.2 and 3.3 respectively.

In Section 3.4, these two kinds of evidence are combined with inferences drawn from the preceding review of soil erosion in general. These are integrated on the basis of the observed and probable effects of different agroforestry practices.

An agroforestry practice is a type of arrangement of agroforestry components (trees, crops, pastures and livestock) in space and time. It is more generalized than an agroforestry system, which is a particular example of a practice, characterized by specified tree and crop species, management practices, physical interactions, and social and economic functioning. The list of agroforestry practices used as a basis for reference is given in Table 2.

3.2 Effects of agroforestry on erosion

3.2.1 General

A review of measurements of erosion under agroforestry and related forms of land use has been made by Wiersum (1984). It would be difficult to improve upon this recent and clear account, and the present summary is largely based upon it. References are given only when they are additional to this source. The review is divided into two parts, the effects of trees on the separate factors of erosion, and observed erosion rates under agroforestry practices.

3.2.2 Effects of trees on the factors of erosion

Rainfall erosivity. Energy is often increased by a high tree canopy, through coalescence of raindrops into larger drops, which can reach their terminal velocity when falling from a canopy more than 30 m high. Anyone who has walked through rain forest during a storm will be aware of this. Higher erosivities have been recorded under forest plantations. Severe erosion has occurred under teak plantations, where the canopy is high and the leaves drop during part of the rains. An increase in erosion by a factor of 2, as compared with forest, has been recorded for a home garden and a multistorey tree garden. It may be supposed that a low and dense canopy would reduce erosivity, but there are no measurements from agroforestry systems. Under alley cropping, although the canopy is low, it is not vertically above the cropped land.

Soil erodibility. It is widely observed that soil structure is of higher grade and more stable, detachability lower and infiltration capacity higher 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. For the practice of trees in fields, under *Acacia albida* in Senegal, no significant differences in structural stability were found between sandy soils beneath and beyond trees. Alley cropping has the potential to maintain

Table 2. Agroforestry practices.

MAINLY AGROSYLVICULTURAL (trees with crops)

Rotational:

1. Planted tree fallow
2. Taungya

Spatial mixed:

3. Trees on cropland
4. Plantation crop combinations:
   - with upper-storey trees
   - with lower-storey tree/shrub crops
   - with herbaceous crops (cf. also 12)
5. Tree gardens:
   - multistorey tree gardens
   - home gardens

Spatial zoned:

6. Alley cropping
7. Boundary planting
8. Trees for soil conservation:
   - barrier hedges
   - on grass barrier strips
   - on bunds etc.
   - on terraces
9. Windbreaks and shelterbelts
10. Biomass transfer

MAINLY OR PARTLY SYLVOPASTORAL (trees with pastures and livestoc

Spatial mixed:

11. Trees on rangeland or pastures
12. Plantation crops with pastures

Spatial zoned:

13. Live fences
    - mainly barrier function
    - multipurpose
14. Fodder banks

TREE COMPONENT PREDOMINANT

15. Woodlots with multipurpose management
16. Reclamation forestry leading to production:
    - on eroded land
    - on salinized land
    - on moving sands

    (Cf. also 2)

OTHER PRACTICES AND SPECIAL ASPECTS

17. Apiculture with forestry
18. Aquaforestry (trees with fisheries)
19. Trees in water management
20. Irrigated agroforestry

organic matter, or limit the rate at which it declines, compared with the almost invariable decline under pure cropping; after six years of maize-leuco alley cropping at Ibadan, Nigeria, topsoil organic carbon was 1.1%, compared with 0.65% when leuco prunings were removed (Kang et al., 1985).

Reduction of runoff. Where trees are planted on soil conservation works, including grass strips, bunds and terraces, this of course reduces runoff and erosion, but no specific added effect can be attributed to the presence of the trees. Barrier hedges appear to be effective in limiting runoff, although there is limited data. Where alley cropping is established along the contour, the tree rows will possibly limit erosion to the same extent as grass barrier strips, but again, data are lacking.

The ground surface cover. Under plantation crop combinations, erosion is substantially reduced where the prunings are laid on the ground surface. In a multistorey tree garden in Tanzania, crop residues were left as mulch, less erosion occurred than under forest. The experiment in which canopy, understorey and litter were selectively removed has been described above (Section 2.5): this is clear evidence that the surface litter cover is far more important than the leaf canopy in controlling erosion. Under trees on pastures, there are two reports of higher erosion than in pure pastures, but no data are given on the reasons for this. Alley cropping can potentially provide surface cover from prunings.

3.2.3 Observed erosion rates under agroforestry practices

Recorded erosion rates under agroforestry practices and other relevant forms of land use are shown in Table 3. If rates of erosion 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:

Table 3. Reported 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	104.8

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

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 practices rather than the intrinsic properties of the practices.

Experiments to record the rate of erosion under alley cropping are in progress at a number of sites, but data presently available are limited. Application of the USLE to 23 land use systems in the Philippines gave low erosion hazard ratings to nearly all systems that included contour-planted Leucaena; "under the alley cropping system with mulching, soil erosion is reduced by 60.2% " (O'Sullivan, 1985). There do not appear to be related field measurements. It may be supposed on a priori grounds that the combination of mulching with the barrier provided by contoured tree rows would effectively control erosion, with the main effect being produced by the soil cover. It is urgent to test this hypothesis, by means of replicated erosion plots under alley cropping with the following treatments (cf. Section 4.2):

- contoured tree rows, prunings retained as mulch;
- contoured tree rows, prunings removed;
- no tree rows, litter mulching using prunings obtained from block-planted trees;
- arable crops only (control).

3.2.4 Summary

The tree canopy frequently does not reduce the erosive impact of falling rain, and may increase it. Soil erodibility is generally lower under agroforestry than pure arable cropping, owing to the better maintenance of soil organic matter. By far the greatest effect in reducing erosion, however, can be achieved by maintaining a ground surface cover of litter, which many agroforestry systems have the capacity to achieve.

Among agroforestry practices, only multistorey tree gardens are by their nature invariably likely to control erosion (but even this could be untrue for a farmer with a passion for clearing away all plant residues!). Other practices, notably planted tree fallow, alley

cropping, plantation crop combinations, multipurpose woodlots and reclamation forestry have the potential to reduce erosion to acceptable levels, given good management.

Trees, and hence agroforestry systems, do not necessarily lead to control of erosion. What matters is the way in which the systems are designed and managed.

In the design of agroforestry systems for erosion control, the primary aim should be to establish and maintain a ground surface cover of plant litter. From the aspect of erosion control alone, maintenance of soil organic matter, and hence of soil physical properties and erosion resistance, is also important. It will not usually be possible to achieve erosion control by tree canopy protection, unless possibly under systems having a low and dense cover.

Similarly in the management of such systems, maintenance of a ground cover of litter is the priority.

3.3 Examples of agroforestry in erosion control

Examples where agroforestry practices have been employed or recommended with erosion control as a major objective include the following (Figures 1 and 2).

Rwanda. Nyabisindu, moist subhumid, bimodal, highland climate. Based on experimental measurements, the Nyabisindu Project recommends the following practices:

- Planting of trees on the upslope sides of barrier strips, which may be of grass or bushes. This leads with time to incipient terrace formation, the tree roots stabilizing the terrace risers. *Grevillea robusta* is the most widely-used species.

- Barrier hedges, 60 cm wide, made up of shrubs, planted either as offset double rows or in a densely-spaced, randomly planted pattern.

In both practices, the function of erosion control is combined with leaf litter for maintenance of fertility and production of timber and fruit as harvest (Neumann, 1983; Nyabisindu, not dated, a and b; Lipman, 1986, pp. 130-1).

Burundi. Bujumbura, moist subhumid, highland climate. Experimental results at the Bujumbura station have shown a clear superiority of soil cover over runoff barriers as a basic approach, leading to recommendations for the following practices:

- Mulching, as the primary recommendation, to be employed wherever cultivation practices permit.

- Barrier hedges, 0.5 m wide, formed of grass and/or shrubs.

- Reforestation of degraded land.

Figure 1. Examples of agroforestry in erosion control.

a. Barrier hedges of double rows of Leucaena with maize, developing naturally into terraces, Philippines; after Celestino (1985) and Pacardo (1985).

b. Leucaena barrier hedges planted at 90 cm spacing in furrows between rows of maize, developing into terracettes, Malaŵi; personal observation.

c. Trees on conservation works, Malaŵi; fruit trees on grass strips, and Leucaena on marker ridges (ridges laid out along contour to guide cultivation ridges below); personal observation.

d. Alternative arrangements for trees on conservation works, Cameroun; fosse de retention - ditch for retaining runoff; arbre d'accompagnement - associated tree; haie productif de stabilisation - productive hedge for stabilization; after Simon (1983).

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

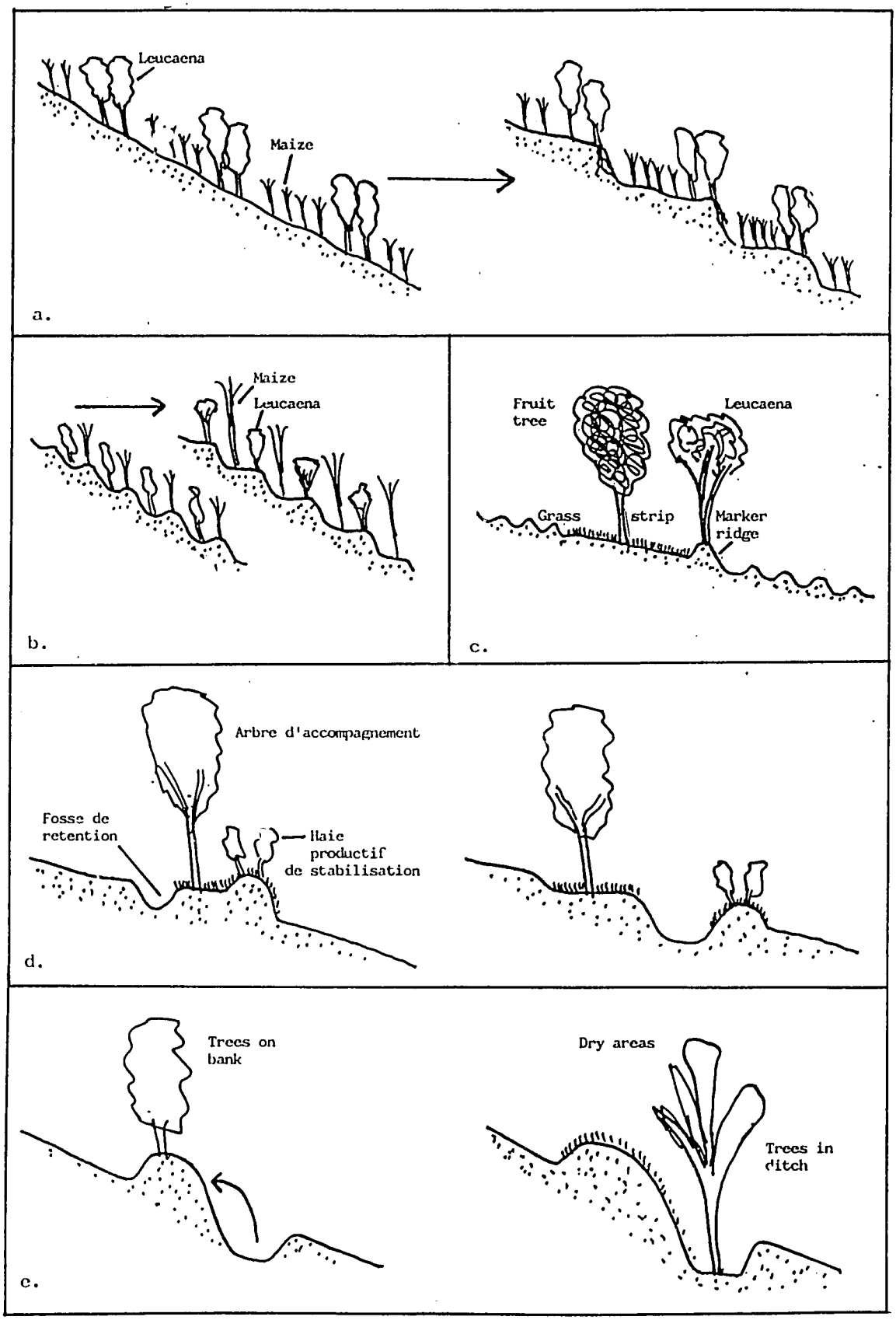
Leucaena
Maize
a.
Maize
Leucaena
b.
Fruit tree
Leucaena
Grass
strip
Marker ridge
c.
Arbre d'accompagnement
Fosse de retention
Haie productif de stabilisation
d.
Trees on bank
Dry areas
Trees in ditch
e.

Figure 1.

Figure 2. Examples of agroforestry in erosion control.

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

b. Trees on risers of irrigated terraces, Nepal; personal observation.

c. Alley cropping 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) and Young (1985b).

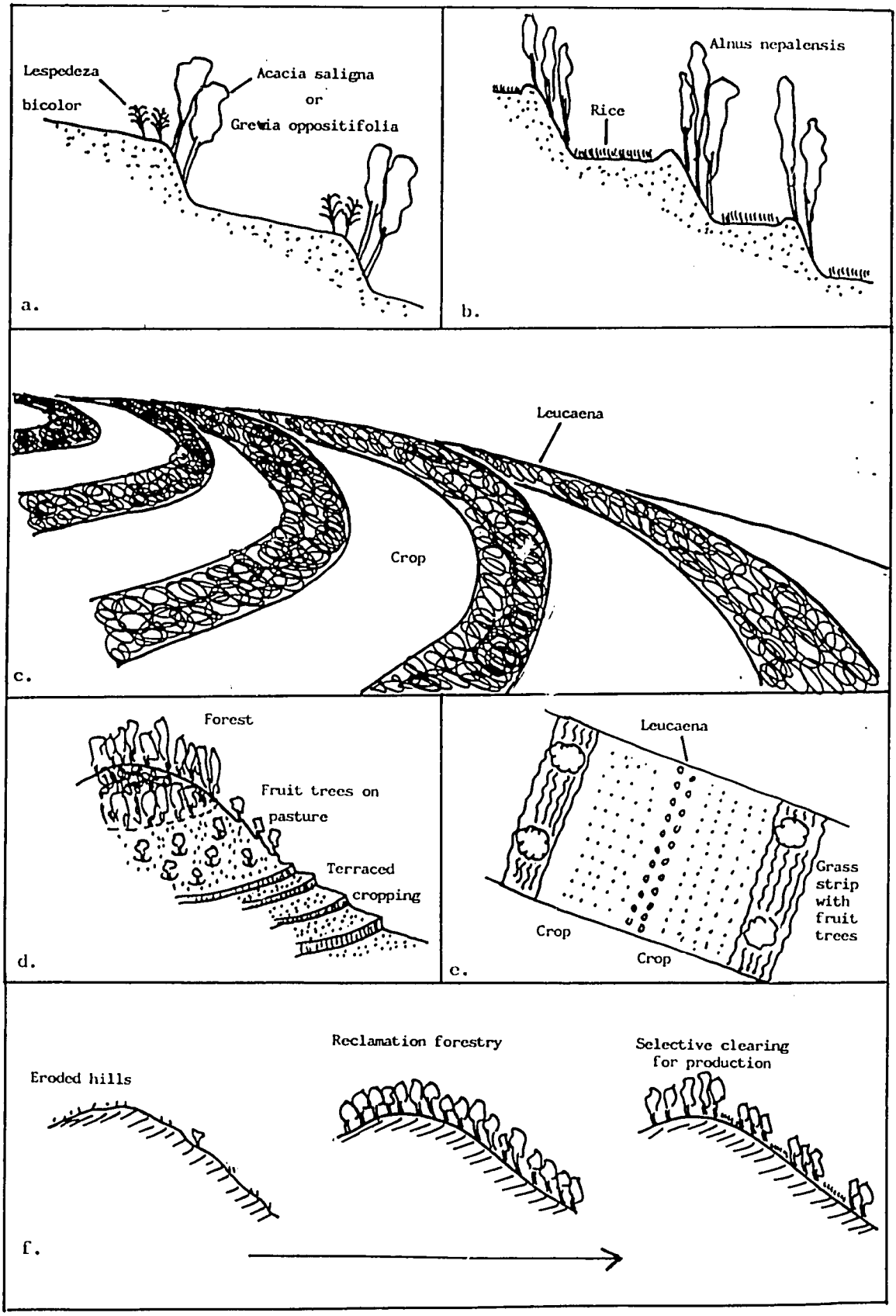
Lespedeza
bicolor
Acacia saligna
or
Grewia oppositifolia
a.
Alnus nepalensis
Rice
b.
Leucaena
Crop
c.
Forest
Fruit trees on
pasture
Terraced
cropping
d.
Leucaena
Grass
strip
with
fruit
trees
Crop
Crop
e.
Eroded hills
Reclamation forestry
Selective clearing
for production
f.

Figure 2.

It is noteworthy that walls, ditches and terraces (banquettes) are explicitly "non-recommended" (Michon and Bizimana, 1984.)

The Philippines. Various locations, mainly humid climates. There are experimental evidence, field experience and recommendations for the following practices:

- Barrier hedges of Leucaena, closely planted in double rows. The hedges are pruned low, and the pruning applied as mulch, with the joint purpose of erosion control and fertility improvement. The establishment of hedges leads with time towards the development of sloping terraces.

- Grass strips with fruit trees or other tree crops. The barrier function is provided mainly by the grass, the trees being for added production.

(Celestino, 1984, 1985; de la Rosa, n.d.; O'Sullivan, 1985; Benge, 1979.)

Also reported is the use of Leucaena branches as pegs for erosion check barriers (Eslava, 1984). However, this practice is inferior to live hedges in many respects.

The success of the Visayas project in obtaining the cooperation of farmers in implementation of conservation measures has been noted above (Section 2.8).

Indonesia. Flores Island and elsewhere, humid or moist subhumid climates, volcanic soils. Over 10 000 ha of steep volcanic slopes have been stabilized since 1973 by contour hedgerows of Leucaena. Indigenous Leucaena species were first used, together with exotic giant Leucaena since 1978. There is progressive development of hedgerows into terraces (Metzner, 1976; Prussner, 1981; Parera, 1983.)

Nepal. Various locations, subhumid monsoonal highland climate. In the steeply sloping terraced areas that make up much of the cropland of the Himalayan foothills (sic), trees are planted on the terrace risers. A fairly dense mass of trees occurs in a few areas, but in many, the cover is sparse and irregular. There is conflict for the use of the prunings, between fodder, fuelwood and mulch (Fonzen and Oberholzer, 1984; E. Fernandes, personal communication.)

India. Shillong, North Eastern Hills Region, humid monsoonal climate, steep slopes. In the local practice of shitfing cultivation (jhum), the former fallow period of 20-30 years has been reduced to 3-6 years. Erosion during the first and second years of cultivation is very severe, typically 150 t/ha/yr. Terracing has been found 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 ("horti-pastoral system").
Lower slope: Terraced arable use.

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

Dehra Dun, subhumid monsoonal highland climate. As part of a long-standing programme of erosion studies at the Central Soil and Water Conservation Research and Training Institute, measurements of runoff and soil loss have been made on plots under alley cropping (Leucaena, Eucalyptus), with crop-only and tree-only plots for comparison. Results are not yet published.

Hyderabad, dry subhumid climate, gentle slopes, ferric luvisols and vertic soils. At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), barrier hedges consisting of four rows of Leucaena, pruned low, have been introduced as an alternative to conventional bunds ("biological bunds").

Negaland, subhumid monsoonal highland climate. The same practice as described for Nepal, trees on terrace risers, occurs under the same circumstance, that in which almost all land is steeply sloping. Alnus nepalensis is a common species, coppiced for fuelwood (Das, 1980).

Tehri District, Uttar Pradesh, humid monsoonal highland climate. A diagnosis and design study, part of the ICRAF collaborative programme, was located in the deep, steeply-sloping valleys with most cropland terraced, typical of large areas of the Himalayan foothills (ICRAF, 1984). Trees are already present on terrace risers to a limited extent. The study recommended research into the following practices:

- alley cropping on treads of rainfed terraces;
- trees on risers of rainfed terraces;
- planted tree fallows for rehabilitation of terraces abandoned because of low fertility;
- planting of trees for fodder and fuelwood in contour strips on village communal lands, with controlled harvesting.

Erosion measurements are included among the management experiments recently started under the All-India Co-ordinated Research Programme in Agroforestry. These studies have been in progress for 1-3 years, and results are not yet available.

In India as a whole, reclamation forestry on eroded land is a widespread, and often successful, practice.

Kenya. Subhumid climates. The standard recommendations for soil conservation include agroforestry to a limited degree, although the main focus is on grass strips and earth structures (Wenner, 1980, 1981). Practices recommended are:

- trees on the embankments of 'fanya juu' structures, a combination of an embankment upslope of a contoured ditch. In drier areas, trees may also be planted in the ditches;
- where grass barrier strips are established, trees, including agricultural tree crops, can be planted on these;
- barrier hedges, of sisal or bushes.

Machakos District: marginal dry subhumid/semi-arid climate. Barrier hedges consisting of single rows of Leucaena, without changing the spacing of intercropped maize, have been established on the Katumani Drylands Research Station.

On the ICRAF Machakos Field Station, the following practices are established on a demonstration basis:

- trees on grass barrier strips;
- trees on 'fanya juu' embarkment and ditch structures;
- trees on margins of terraces;
- barrier hedges.

Of interest as an historical forerunner of modern agroforestry is the suggestion for planting trees as contour-aligned rows to control erosion made in Leakey (1949).

Cameroun. West Cameroun, subhumid climate. The following practices have been tested and are recommended:

- .stabilization hedges, consisting of single or double rows of shrubs, planted on embankments; functions of the hedges are to check runoff, filter out the soil in runoff, enrich the soil by recycling nutrients, and diversify production;
- supplementary trees (arbres d'accompagnment), on contoured grass strips; species include quinine, coffee, banana, fruit trees and timber species;
- alley cropping: bushy hedges at 4-8 m spacing.

It is recognized that the herbaceous plants and shrubs, coupled with ditch and embankment structures, perform the main barrier function, the trees being for additional production (Simon, 1983.)

Malaŵi. Various areas, especially Ntcheu District: subhumid climate. Demonstration plots were established in the early 1980s, following which two practices are being recommended and adopted by farmers, although never ratified by controlled experimental research. Adoption has occurred particularly in one district, Ntcheu, where there is much cultivation of sloping land. The practices are:

- Grass barrier strips, 2 m wide, are a recognized means of erosion control on gentle to moderate slopes, with harvest of cut-and-carry fodder; it is now recommended to add fruit and timber trees to these, for additional production.

- A practice at present unique to Malawi, the planting of single rows of leuco between every row, or every 2 rows, of maize, the latter contour-planted on cultivation ridges. The rows of maize remain at the standard recommended spacing of 90 cm, and thus the rows of leuco are 90 or 180 cm apart. The trees are directly seeded. They are pruned to 50 cm before planting and at least once during the growing season, but at the time of harvest the appearance of a leuco thicket within which are maize plants. This practice is being tried on level ground, for fertility improvement, and on slopes of up to 25, for combined erosion control and fertility purposes. On steep slopes, the practice leads after only a few years to the development of terracettes, with risers formed of leuco stems. This practice is locally called "alley cropping", although it is more akin to closely-spaced barrier hedges (personal observation).

Ethiopia. Gojam region, moist subhumid climate. In a consultant's report for the establishment of trials and demonstrations, in which erosion control on steeply-sloping land is the primary objective, the following practices are recommended:

- Improvement of degraded pastures by planting fodder trees (*Robinia pseudoacacia*, *Acacia saligna*) at staggered 5 x 5 m spacing, the trees to be planted on individual platform terracettes.

- *Acacia saligna* and *Grewia oppositifolia* planted on risers of existing terraces on cropland.

- *Erythrina abyssinica*, in association with grasses, on bunds.

(von Carlowitz, 1986)

Vietnam. North of Hanoi, humid monsoonal climate. In this area, rounded hills which rise above swamp rice land have been severely eroded through long periods of intensive use. Reclamation forestry using leguminous trees, to check further erosion and bring about soil improvement, to be followed in time by mixed production and conservation based on contour rows of trees and crops, has been recommended (Poulsen, 1984; Young, 1985b).

3.4 Review of agroforestry practices in erosion control

3.4.1 Introduction

The inferences from the review of the cause of erosion, experimental evidence on erosion rates, and examples of the use of agroforestry practices, can be brought together in a summary of the actual or

possible effectiveness of agroforestry as a means of erosion control. This will be done in terms of the different agroforestry practices (Table 1), commencing with those in which erosion control is the primary aim and proceeding towards those in which it is subsidiary to other purposes.

3.4.2 Barrier hedges

These are dense, narrow hedges, planted along the contour and kept low by repeated pruning. Rows are narrow, ranging from 5 cm (at ground level) up to about 1.0 m. The inter-row spacing varies with slope angle but is typically close, from 4 m down to as little as 1 m. Alternatives are: (i) a single row, with very close within-row spacing, so that the stems are almost touching; (ii) a double row; (iii) dense random spacing of bushes. Planting can be by direct seeding (especially for the single-row type) or by seedlings. The hedges are pruned before planting crops, and the prunings placed on the soil surface. One to three further prunings are necessary during the crop growing season, although at and after harvest, the hedges can be allowed to reach about the same height as the crop.

In the case of narrow single-row hedges, it is possible not to modify the spacing of the crops at all; the hedge occupies the space between crop rows. This is a valuable feature where slopes are steep and hedges must be closely spaced. Broader hedges lead to loss of one crop row, and hence some 10-20% of crop area, a loss which must be made up by higher yields.

The functioning of this practice includes the following elements:

- a barrier to runoff, provided by the stems and accumulation of litter against them;
- the soil cover provided by the prunings, particularly during crop planting and early growth stages when the cover would otherwise be low;
- the associated improvement to fertility produced through the decay of shrub prunings;
- the natural development of the barriers into terraces, through accumulation of soil upslope of the hedges and stabilization of the risers by stems and roots.

Present evidence suggests that the cover function is more important than the barrier function. Therefore this practice is likely to be substantially less effective if the prunings are removed, for fodder or fuel.

Leucaena has been most frequently employed. It is efficient as a barrier and for fertility improvement. Its cover function is less than ideal owing to rapid leaf decay. *Grevillea robusta* forms a dense hedge when pruned and has slower leaf decay, and *Cassia siamea* is another possibility.

This practice is best established for the humid and moist subhumid zones, where it has been found effective in erosion control, and at the

same time to provide equal or womewhat higher yields of interplanted maize and cassava. It shows some promise for the drier subhumid and semi-arid zones, but requires testing before it can be confidently recommended. It can be used on slopes ranging from gentle to steep. It would seem a possibility for areas of gently-sloping vertisols, although there is no evidence.

Research is needed into the effects of root competition, particularly for closely-spaced rows. It is desirable to identify other tree species which effectively combine the formation of a dense barrier with soil cover and fertility enhancement, coupled with tolerance to repeated pruning, suited to different climates.

In the design and management of barrier hedges, it is important to stress the importance of the soil cover provided by tree litter. The barrier function alone is likely to be much less effective, and hence this practice may not be effective where there are other demands for the prunings. The practice has a moderately high labour requirement for pruning.

3.4.3 Trees on soil conservation works

i. 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 the case for many fruit trees, the spacing should be moderately wide, e.g. 10 m, to avoid reduction in grass density. The trees play no direct part in erosion control, their function being to make productive use of the land devoted to such control.

The main design precaution is to avoid the use of trees which cause reduction in density of the grass sward.

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

ii. Trees on earth structures for erosion control. Trees or shrubs can be planted on any of the earth structures employed for erosion control: bunds, storm drains, "fanya juu" banks and ditches, marker ridges, and possibly grassed waterways. The trees are usually planted on the banks, but in dry areas can also be in the ditches.

The functions of this practice can include any of the following:

- to stabilize the structures, through rooting systems;
- in the case of shrubs, possibly to add to the runoff barrier function;

- to provide limited soil cover, with fertility improvement, to adjacent cropland;
- to make productive use of land devoted to the control structures, and thus enhance their acceptability;
- a function, partly psychological, of making the control structures permanent-----once the trees are established and productive, the erosion control structures are likely to remain.

Many different species can be employed, according to requirements for fuelwood, fodder, fruit, or litter for fertility enhancement. Cassia siamea has good survival, grows over a substantial climatic range, produces fuelwood and is suitable for fertility improvement. Grevillea robusta combines the functions of a shadetree to adjacent perennial crops with fuelwood production. Leucaena is again widely employed. Fruit trees can be any that are climatically adapted and locally in demand.

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. There are no specific environmental preferences.

iii. Trees on risers of terraces. In sloping lands that are already terraced, there appear to be benefits from planting a dense tree cover on terrace risers. The trees are either pruned or coppiced. Potential functions are:

- to stabilize the terrace risers, and reduce the need for maintenance;
- fertility improvement on the terrace treads;
- production, of fuelwood, fodder or fruit.

Species can be varied according to climate and local needs. In India and Nepal, Grewia oppositifolia and Alnus nepalensis are widely used.

The practice appears to be suited to any 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 production, fertility improvement or both to this type of system, thereby retaining soil conservation whilst enhancing production.

3.4.4 Alley cropping as a means of erosion control

The alley cropping system as a whole is a large subject, in which there is both a high potential and many design and management problems

requiring research. Reviews have been written by Kang et al. (1984), Ssekabembe (1985) and Huxley (in preparation). What is here relevant is the specific potential for erosion control.

Most experimental work to date on alley cropping has been conducted on level to gently-sloping land, and with the primary objectives of establishing its capacity for improvement of fertility. However, the practice appears to have substantial added potential as a means of erosion control. Viewed in this light, it consists essentially of strips of woody perennials, with or without grass beneath; the trees yield a high biomass production, and are frequently pruned. With these features, and if the tree rows are laid out along the contour, the following functions can be expected:

- a check to runoff, and increase in infiltration, through the barriers provided by the tree rows;

- a substantial reduction in erosion if the prunings are placed as mulch on adjacent belts of crops;

- the improvement of fertility already established for some systems;

- possibly also productive functions from the trees, although these may conflict with use for fertility;

- progressive development towards sloping terraces may occur, as a result of accumulation of soil upslope of the tree rows.

Apart from the many problems of design and management inherent in alley cropping, particularly related to interactions at the tree/crop interface, its use on sloping land for erosion control raises the question of spacing of tree rows. From considerations not related to erosion, the preferred spacing between tree rows is typically 4-8 m. If the tree rows are aligned along the contour, a spacing of 8 m spacing is close enough to control erosion on gentle to moderate slopes, up to c. 15° (27%), whilst 4 m may prove to be adequate on steep slopes (up to 25°, 47%), given the combined effects of mulch cover and barrier tree rows. From an erosion control viewpoint, each tree row should be set out along the contour, which means that the inter-row spacing will not be constant; but this can be dealt with by discontinuing or adding a row where the spacing becomes too narrow or too wide respectively.

From a general point of view, alley cropping has been shown to be effective in humid and moist subhumid climates, whilst it is being tested for the dry subhumid and semi-arid zones. There is no <u>prima facie</u> reason why it should not be effective for erosion control in any of these rainfall zones, in both lowlands and highlands. As noted above, it can be designed to give erosion control on slopes of up to 25° (47%). It should be tested for the special case of vertisols, where the potential to combine maintenance of soil organic matter with soil cover and barrier functions should prove valuable.

The apparent high potential of alley cropping as a means of erosion control, coupled with the paucity of experimental data, means that research into this aspect is a priority.

The design of research into alley cropping as a means of erosion control is considered further in Section 4.2.

The potential of alley farming on pastures is discussed below under sylvopastoral systems.

3.4.5 Plantation crop combinations, multistorey tree gardens and home gardens

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 "shade tree" systems, such as Cordia alliodora with coffee), another tree crop (as in coconut with cocoa, or coffee with bananas), or a herbaceous crop. The primary tree crop may be spaced either randomly, as is common in indigenous systems, or regularly, as on plantations.

Both inference and evidence point to the fact that such systems can be an effective means of erosion control, provided that a ground cover of litter is maintained. The target should be a litter cover of at least 60% throughout the period of erosive rains.

Conversely, even dense plantation crops are not effective if the ground is kept bare, for example through chemical weed control. However dense may be the tree canopy, it is maintenance of a surface litter cover that should be the aim in management for erosion control.

The related practices of multistorey tree gardens and home gardens consist of a variety of woody and herbaceous crops, grown together in a dense, random spacing. Given the combination of dense vegetation with litter production all the year round, erosion control is virtually inherent in such systems. An exception might occur if there were excessive harvesting of the herbaceous plants and clearance of litter.

These practices are of particular value in that they provide sustainable kinds of land use in humid to moist subhumid environments, where rainfall erosivity is high and steep slopes common.

3.4.6 Sylvopastoral practices

It is not always sufficiently recognized that soil erosion on pastures is often more severe than on croplands. Severe sheet erosion and gullying are both common. The erosion is initially caused by degradation of the vegetation cover through over-grazing, and in the case of gullying, lowering of the water table, a complex of processes which in the semi-arid zone is commonly referred to by the much misused word "desertification". Erosion and pasture degradation are common both in semi-arid lands dependent primarily on grazing, and on land used for pasture in areas of mixed farming.

Sylvopastoral practices include trees on pastures (e.g. Acacia albida and other acacia species), alley farming on pastures, trees with plantation crops (e.g. livestock under coconuts, sheep under rubber), live fences and protein banks. (The use of windbreaks and shelter belts for control of wind erosion is excluded from this review.) It would be of great value if ways could be found of applying such practices to the control of erosion on pasture land.

If this were attempted simply by planting trees, in whatever spatial arrangement, without other changes to the management of degraded pastures, it would not be successful. The basic tenets of pasture management, such as the restriction of livestock numbers to within capacity and rotational grazing with rest periods, are a prerequisite to erosion control as to any other aspect of sylvopastoral systems. For example, a system of alley farming on pastures would supply only the less effective barrier function if litter were consumed by animals as soon as it fell.

Given good basic pasture management, however, trees might contribute to erosion control in a number of ways. First, if the grass sward is better beneath trees than beyond, as occurs in some instances with Acacia albida, then this will contribute to reducing raindrop impact and runoff. Secondly, it may be possible to use alley farming or live fences in controlling livestock movement, thereby contributing to rotational grazing.

However, the greatest potential is possibly 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 undigestible. This can be through direct browse, as by sheep, goats and game animals, or through cut-and-carry browse. 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.

3.4.7 Planted tree fallow and taungya

Planted tree fallow is a practice intended to simulate the effects of shifting cultivation but with the tree fallow consisting of planted species, selected for their soil enrichment capacity, useful products, or both. 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, however, in a system in which a mulch cover was maintained by some means during the non-fallow period.

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, but neither the loss of fertility nor effects on subsequent tree growth have been shown to be serious.

3.4.8 Other agroforestry practices

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

The practice of trees on cropland, where these are widely spaced, is not likely to have any appreciable effect on erosion. Biomass transfer, the carrying of tree litter from woodland to cropland, improves fertility but cannot have more than a marginal effect on erosion. The remaining practices in Table 2 are not relevant to erosion control.

4 RESEARCH CONSIDERATIONS

4.1 Objectives of research

The objectives of research into agroforestry in erosion control should be:

i. For those agroforestry practices and systems for which there is inferential, or limited experimental, evidence that they are effective as a means of erosion control, to establish whether this is in fact the case.

ii. To build up knowledge of the processes by which specific agroforestry practices achieve control of erosion; by this means, to assist in the design of specific systems for this purpose; and to test the improved designs.

iii. To compromise and reconcile designs that are optimal for the purpose of erosion control with those that meet other design requirements.

iv. To test the response of farmers to erosion control by means of agroforestry.

v. To evaluate, on environmental, economic and social grounds, the overall effectiveness of agroforestry systems on land with an erosion problem.

Approaches to research that can contribute to the achievement of these aims are:

- on-station experimental research;
- on-farm trials;
- broadly-based studies, including data from on-station and on-farm trials and from other sources.

Objectives i and ii are primarily matters for on-station research. With respect to no. i, until it can be stated with confidence that a given practice does what is claimed for it, the time is not ripe for extension to farms.

No. ii is based on detailed, controlled studies of the functioning of erosion processes under tree/crop and tree/pasture mixtures. It is only when such basic knowledge exists that it becomes possible to design agroforestry systems in a scientific manner, as compared with the less efficient approach of trying a wide range of designs to "see if they work".

Objective iii requires a combination of on-station with on-farm studies, since the design requirements refer not only to the scientific functioning of the designs but also to their role within the land use system as a whole. Objective iv is necessarily approached by on-farm trials. No v, evaluation, requires broadly-based studies, incorporating data from trials but also economic, social and policy aspects.

Most agroforestry research is environment-specific. That is, it cannot be assumed that a practice or system which is effective in one combination of climate, landforms, soil and vegetation will be equally effective in another. Thus each practice needs to be tested for the major climatic zones, the main soil types present in areas to which the research relates and, where relevant (sylvopastoral systems), for vegetation types.

4.2 Design of research

The approach to the design of on-station research may be illustrated by an example, studies on erosion control under alley cropping. The aims of such studies should be

- to determine whether losses of soil material, organic matter and nutrients under alley cropping fall below limits regarded as acceptable;
- to find the best spacing and management practices from the point of view of erosion control (to be compared and reconciled with those found to be best for crop yield and other aspects);
- as a guide to the design of spacing and management practice, to isolate the respective effects of the barrier function provided by the tree rows and the soil cover function provided by the tree mulch;
- to determine values of the conservation practice factor (USLE) or energy interception and crop ration (SLEMSA) for specified alley cropping systems.

The standard US erosion plot, 22 m long, is adequate for the purpose, although the southern Africa plot, 30 m long, or 50 m plots may be preferable. A 22-m plot would permit, for example, three tree rows 2 m wide plus three crop alleys 5 m wide. The design could include the following treatments, replicated:

i. alley cropping, prunings laid on crop rows, using species, spacing and management believed optimal for the site;

ii. alley cropping as above, but with one or more alternative inter-row spacings, narrower and/or wider;

iii. possibly one or more alley cropping plots using tree species with slower or faster leaf decay, or with different timing of application of prunings;

iv. as in i, but with prunings removed, to demonstrate the effect of barriers without cover;

v. no tree rows, but with a mulch equal in quantity to that in i (brought in from trees grown outside the plot), to demonstrate the effect of cover without barriers;

vi. continuous tree cover, of same species as those used in alley cropping, to investigate whether soil loss under alley cropping is reduced to an amount close to that under the tree component alone;

vii. arable cropping (control).

It is of the utmost importance that measurements should include analysis of the organic matter and nutrient contents of eroded material, in addition to the mass of soil lost.

Similar research designs could be drawn up for study of the other agroforestry practices noted in Section 3.4.

4.3 The need for research

Three conclusions from the above review may be placed in conjunction.

First, there is substantial and growing evidence that erosion is the cause of considerable losses of crop production in the tropics. The almost inevitable growth of population over the next 25 years will make this problem more serious and the economic and social need for its control more urgent. The problem is greatest in what may be called sloping lands, those areas in which 50% or more of potential arable land lies on moderate to steep slopes.

Secondly, it has been shown that a number of agroforestry practices are likely to have the potential effectively to reduce soil erosion to acceptable rates, those at which crop yields will not be substantially reduced. This conclusion holds true with respect to erosion control when considered in isolation. However, its implications are strengthened when considered in conjunction with the capacity of agroforestry for the maintenance or improvement of soil fertility (covered in Part II of this review), as well as the known potential for provision of goods and other services.

Thirdly, it has been emphasized that much of the evidence for the preceding conclusion is indirect or inferential. Controlled experimental data on rates of erosion under agroforestry systems, and their effects on productivity, is sparse, relative to that normally considered necessary to establish the soundness of a land use practice.

Putting these conclusions together, there is a large and growing problem of erosion, a considerable apparent potential for controlling this by means of agroforestry, and a paucity of experimental data to confirm this potential. It is hard to imagine a combination of circumstances which so clearly indicates the need for research!

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