# Maintenance of Soil Fertility for Sustainable Production of Trees and Crops Through Agroforestry systems

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## ABSTRACT

Sustainability is essentially continued plant production combined with conservation of the resources on which that production depends. Maintenance of soil fertility is the major element in sustainability. Agroforestry covers a wide range of land use systems in which trees and crops are grown on the same land, in spatial or rotational combinations. The traditional separation of agriculture from forestry is inappropriate : most farmers in the tropics practice agroforestry to some degree. Agroforestry has both productive functions (for fuelwood, fodder, fruit, etc.) and service functions, the most important of which is maintenance of soil fertility. The major effects of trees on soil fertility are control of erosion, maintenance of soil organic matter and physical properties, nitrogen fixation, improved uptake of nutrients, and nutrient recycling. In erosion control a key feature, contrasting with conventional methods, is the capacity to combine plant production with conservation. The most promising agroforestry technologies for soil conservation are multistorey tree gardens, plantation crop combinations and hedgerow intercropping, the last-named particularly on sloping land. A computer model, SCUAF, has been developed, for estimating soil changes under agroforestry. An agenda for soil-agroforestry research is proposed, in the form of 10 hypotheses. If the high apparent potential of agroforestry can be confirmed by further research, there is opportunity for a major contribution to sustainable plant production in the tropics.

## Introduction

The argument presented here is that agroforestry has a high potential for sustainable plant production, particularly but not only through its contribution to soil conservation. As a basis for discussion, it is first necessary to set out what is understood by sustainability and soil conservation, and then to indicate the nature of agroforestry and the range of practices which it includes. It will be shown that, with good design and management, agroforestry can achieve conservation of soil fertility whilst at the same time maintaining or increasing production of food and other plant products.

This account is based on an extended review, *Agroforestry for Soil Conservation* (Young, 1989a), in which supporting evidence and references are given.

## Sustainability and soil conservation

Sustainability, or sustainable land use, may be defined as land use in which production is maintained at or above the level of the present, combined with conservation of the natural resources on which continued production in the future depends. In short :

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SUSTAINABILITY = PRODUCTION + CONSERVATION

There is a key difference from the concept of environmental conservation which came to the fore in the late 1960s. The environmental movement placed emphasis on conservation of resources. In sustainability, production comes first. Only when current needs for food, other essentials and a cash income have been met can attention be given to conservation. Certainly, farmers recognize that production in the future depends on soils and other natural resources; but when you are poor and dependent on the land, production of this year's needs for the family must take priority.

There are wide-ranging socio-economic considerations involved in the achievement of sustainability. Here we shall be concerned mainly with environmentally-related aspects, how to combine maintenance of plant production with conservation. The resources to be conserved include those of forests, rangelands and water, as well as avoidance of pollution. However, for areas under arable cultivation, soil conservation is the primary concern.

Formerly, soil conservation was equated with prevention of erosion. It is now recognized that equally important are maintaining the organic matter status and physical properties of the soil, ensuring an adequate nutrient supply, and preventing the buildup of toxicities (acidity, salinity). This view can be taken further by saying that soil conservation is essentially maintenance of fertility——for which control of erosion is one necessary, but by no means sufficient, condition.

## Agroforestry and plant production

Agroforestry is a collective name for land use systems in which trees or shrubs are grown in association with agricultural crops, or pastures and livestock, in a spatial arrangement, a rotation, or both, and in which there are both ecological and economic interactions between the trees and other components of the systems.

Distinctive features of agroforestry are the presence of trees, and the ecological interactions between these and the other components, which take place through the medium of microclimate, soils and biota. Examples of interactions are reduction in soil surface temperatures and evaporation through shading, recyling of nutrients from plant to soil by decomposition of tree litter, and effects of trees on weeds and pests.

A misconception still sometimes encountered is to regard agroforestry as consisting of only one or a few practices. An *agroforestry technolygy* is a distinctive arrangement of components in space and time. An *agroforestry system* is a specific local example of a technology, characterized by plant species and arrangement, management, products, and socio-economic functioning. There are many thousands of agroforestry systems, which can be grouped into some 20 distinct technologies (Table 1). This wide range is one of the strengths of agroforestry; it means that where one technology is found to be inappropriate to the environment or needs of an area, another can be identified that is suitable.

Agroforestry systems have both productive and service functions. Production comes from at least two plant components: the trees may produce fuelwood, fodder, fruit and a variety of other products, whilst the crops may yield food and non-food agricultural products. In addition there may be livestock products from the system. Because of the presence of trees, plant production from agroforestry systems is intrinsically more diversified than from agriculture.

Most smallholder farmers in the tropics practice agroforestry to some degree (Nair, 1989; Lundgren and Young, in press). This may seem a surprising statement, as we are accustomed to thinking of 'f'arming' as synonymous with 'agriculture'. However, it is unusual to find small farms where there are not some trees on the land; the main exceptions occur in swamp rice farming. The trees are either planted or deliberately preserved from

**Table 1 Agroforestry technologies (Young, 1989a)**

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|---|
| MAINLY AGROSYLVICULTURAL (trees with crops) |
| Rotational: |
| Shifting cultivation |
| Improved tree fallow |
| Taungya |
| Spatial mixed: |
| Trees on cropland |
| Plantation crop combinations |
| Tree gardens |
| Spatial zoned: |
| Hedgerow intercropping |
| Boundary planting |
| Trees on erosion-control structures |
| Windbreaks and shelterbelts (also sylvopastoral) |
| Biomass transfer |
| MAINLY OR PARTLY SYLVOPASTORAL (trees with pastures and livestock) |
| Spatial mixed: |
| Trees on rangeland or pastures |
| Plantation crops with pastures |
| Spatial zoned: |
| Hedgerow intercropping (systems with livestock) |
| Live fences |
| Fodder banks |
| TREE COMPONENT PREDOMINANT (cf. also taungya) |
| Woodlots with multipurpose management |
| Reclamation forestry leading to multiple use |
| OTHER COMPONENTS PRESENT |
| Entomoforestry (trees with insects) |
| Aquaforestry (trees with fisheries) |

clearing, and in both cases they are consciously managed, e.g. by pruning for fodder and fuelwood. The extent of the agroforestry element is sometimes less than it was in earlier times, through land pressure and clearance. Modern agroforestry seeks to reverse this trend.

The services provided by agroforestry include shade (from sun, for animals and men), shelter (from wind), water management and fencing. By far the most important service function, however, is that of soil conservation.

## Agroforestry for soil conservation

### 1) Control of erosion

Trees can be employed in erosion control in supplementary and direct ways. Supplementary use refers to the planting of trees on conventional soil conservation works, such as earth structures and grass strips. In direct use, the tree component itself is the means of controlling runoff and soil loss.

In supplementary use, trees can be planted on ditch-and-bank structures, grass strips and terraces. The trees serve to stabilize the structures, through their root systems, and to make productive use of them. Conventional soil conservation works occupy 10-20% of the land, sometimes more, reducing the area available for cropping. This is a strong disincentive to adoption by farmers. However, if trees are planted there can be plant production, e.g. of fuelwood, fodder or fruit, from the area under conservation works. For example, in Rwanda, *Grevillea robusta* are grown for timber on conservation banks. On ICRAF's Machakos (Kenya) Field Station, a dryland area (rainfall 700mm bimodal, Haplic Lixisols), six species of fruit trees have been planted in the ditches of the bank-over-ditch structures that are the standard methods of conservation in Kenya; all are fruiting well, and benefit from what is effectively a form of sunken planting. On terraced steep slopes in Nepal and Himalayan India, trees are grown on the terrace risers and pruned for fodder.

For the direct use of trees and shrubs, an approach applicable to steeplands in humid environments is that of dense, mixed systems, including multistorey tree gardens and plantation crop combinations. Several species of trees, often including agricultural tree crops, are densely interplanted, sometimes with a herbaceous layer beneath. The heavy litter fall from these plants provides a ground cover which is more than sufficient to control erosion. Combinations of coconuts with coffee and/or cacao, for example, are to be found in The Philippines and Nigeria.

The socond approach is the technique of hedgerow intercropping (also called, less accurately, alley-cropping). Dense hedgerows are planted parallel to the contours, with agricultural crops grown in the alleys between. The hedgerows are pruned low, about 30-60cm, to avoid competition for light. Experimental evidence for the effectiveness of this technique is sparse but invariably positive (Lal, 1989; Young, 1989a, 53-58; Kiepe and Young, in press). One advantage is that hedgerows take up less land than earth structures or grass strips (Table 2). Another is the added benefits to soil fertility arising from the hedgerows (see below), and a third, the opportunity for plant production from the hedge component, of fodder (e.g hedgerows of *Leucaena leucocephala*) or fruit (e.g. hedgerows of guava, *Psidium guajava*).

### 2) Maintenance of soil fertility

A forest cover will maintain or improve soil fertility, whereas continuous arable cropping, without external inputs, will normally degrade it. Shifting cultivators know and make use of the beneficial effects of trees on soils, and the same capacity is employed in reclamation forestry. The basis for believing that agroforestry systems may have the potential to sustain soil fertility lies in the inclusion of trees.

Trees improve soils through a wide range of processes, including augmentation of inputs, reduction of losses and improvement of soil physical, chemical and biological conditions (Table 3). Among these processes, the most important are:

- maintenance of soil organic matter, through the addition of tree litter fall, prunings and root residues (Young, in press);
- nitrogen fixation, by some leguminous and a few non-leguminous tree species (Dommergues, 1987);
- improved uptake of nutrients through the fine roots and mycorrhizal systems of trees, and possibly also by deep root systems which penetrate the B/C and C horizons;
- the recycling of nutrients that would otherwise (in agricultural systems) be lost through leaching;
- the reduction of losses of organic matter and nutrients that would otherwise occur in runoff and eroded sediment, a consequence for soil fertility of the capacity to control erosion noted above.

The potential for nutrient recycling is of the highest importance. It is known from ecological studies that in natural forest, the quantity of nutrients that enters and leaves the system annually is only some 5-10% of that which is recycled between plant and soil (e.g.

**Table 2 Processes by which trees improve soils (Young, 1989a). Not all of the effects listed are proven**

Processes which augment additions to the soil:

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

Processes which reduce losses from the soil:

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

Processes which affect soil physical conditions:

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

Processes which affect soil chemical conditions:

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

Soil biological processes and effects:

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

Golley *et al.*, 1975). In agricultural systems, by contrast, nutrient losses through leaching and erosion can be of the order of 40% of those recycled (Lelong *et al.*, 1984; Pieri, 1989). It is believed that agroforestry systems can achieve a value in between these limits.

Evidence comes mainly from two systems, hedgerow intercropping and plantation crop combinations. A study of hedgerow intercropping at Ibadan, Nigeria, showed improved soil properties, both physical and chemical, following hedgerow intercropping than under maize-only controls, whilst similar results have been obtained from Malawi, Sri Lanka and elsewhere (Kang *et al.*, 1985; Yamoah *et al.*, 1986; Chiyenda and Materechera, 1989; L.

**Table 3 Areas taken up by soil conservation measures and by cropping, ICRAF Machakos Field Station, Kenya**

| Type of conservation | Area under Crops % | Area under Conservation % | Products from land under conservation works |
|---|---|---|---|
| Bank-over-ditch | 67 | 33 | Fruit, grass fodder |
| Terraces | 78 | 22 | Fuelwood, grass fodder |
| Trees on grass strips | 81 | 19 | Timber, fuelwood, fodder |
| Hedgerow intercropping | 84 | 16 | Tree fodder, fuelwood |

Weerakoon, personal communication). At the ICRAF Machakos Field Station, Kenya, hedge root systems of *Leucaena leucocephala* and *Cassia siamea* have been observed to extend 4m across cropped alleys to beyond the adjacent hedgerow, and the same feature has been observed with *Gliricidia sepium* in Indonesia (van Noordwijk *et al.*, in press).

A contributory factor to efficiency of recycling is the opportunity offered in the management of hedgerows to synchronize release of nutrients from decaying prunings with uptake requirements of crops. This can be done through choice of hedge species (with fast- or slow-decaying litter), timing of pruning, and manner of addition of residues to the soil. The achievement of this management goal forms the synchrony hypothesis being studied under the Tropical Soil Biology and Fertility (TSBF) program (Ingram and Swift, 1989).

The second system is that of plantation crop combinations. In many parts of central and southern America, coffee and cacao are intercropped with trees referred to as shade trees, although in fact they perform many other functions (Beer, 1987). The most complete nutrient cycling study is for cacao (*Theobroma cacao*) with *Cordia alliodora* and *Erythrina poeppigiana* in Costa Rica. The *Cordia* are allowed to grow into tall trees and felled for timber, whilst the *Erythrina* are pruned annually and the prunings laid on the soil. One system studied is quite heavily fertilized, and it has been shown that for all the major nutrients, the amounts recycled in litter and prunings from the cacao and trees exceed those applied as fertilizer (Fassbender *at al.*, 1988).

### 3) Agroforestry technologies for soil conservation

A feature to stress is that the beneficial effects on soil fertility reported for agroforestry systems are obtained without loss of plant production. In some cases, crop yields under hedgerow systems are actually higher, in terms of yields per total area, than under crop-only controls. In others, a small loss in crop production is economically compensated by returns from the harvest of fuelwood or fodder from the hedgerows. Table 4 is a summary of those agroforestry technologies which have a proven or apparent potential for soil conservation.

## Modelling soil changes under agroforestry

A computer model has been developed, Soil Changes Under Agroforestry or SCUAF, designed to estimate the changes in soil properties under specified agroforestry systems within given environments (Young and Muraya, in press). The soil properties and processes covered by Version 2 of the model are soil organic matter (represented by carbon), nitrogen cycling and changes in the rate of erosion. The user enters data on the environment (climate, slope, soil), initial soil conditions, initial plant growth, and the agroforestry system, including areas covered by trees and crops, and which parts of these two plant components are harvested from the system. Values for plant-soil processes can also be entered, e.g. humus decomposition constants, leaching losses. Finally, there are plant-soil feedback factors, which model the consequences for plant growth of changes in soil carbon and nitrogen, and

**Table 4 Ten hypotheses for soil-agroforestry research (Young, 1989b)**

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|---|---|
| 1 | Agroforestry systems can control erosion, thereby reducing losses of soil organic matter and nutrients. |
| 2 | Agroforestry systems can maintain soil organic matter at levels sufficient for soil fertility. |
| 3 | Agroforestry systems maintain more favourable physical properties than agriculture, through a combination of organic matter and the effects of tree roots. |
| 4 | Nitrogen-fixing trees can substantially augment nitrogen inputs into agroforestry systems. |
| 5 | The tree component in agroforestry systems can increase nutrient inputs, both from the atmosphere and from the B/C soil horizons. |
| 6 | Agroforestry systems can lead to more closed nutrient cycling than under agriculture, and so to more efficient use of nutrients. |
| 7 | The cycling of bases in tree litter can help to check acidification of soils. |
| 8 | Agroforestry systems offer opportunities to augment soil water availability to crops. |
| 9 | Agroforestry can be incorporated into systems for the reclamation of degraded soils. |
| 10 | In the maintenance of soil fertility under agroforestry, the role of tree roots is at least as important as that of their above-ground biomass. |

of loss of soil depth through erosion.

Where data are not available, the model supplies a set of default values, best estimates for the environmental conditions specified (e.g. default values for leaching are higher for higher rainfall and sandy soils). Comparisons between agroforestry and agriculture can be made, by specifying the latter as an 'agroforestry system' with 0% trees and 100% crops.

Figure 1 is an example of an output from SCUAF. It shows the estimated effect on the soil of 8 years of maize monoculture followed by 8 years of hedgerow intercropping, taking

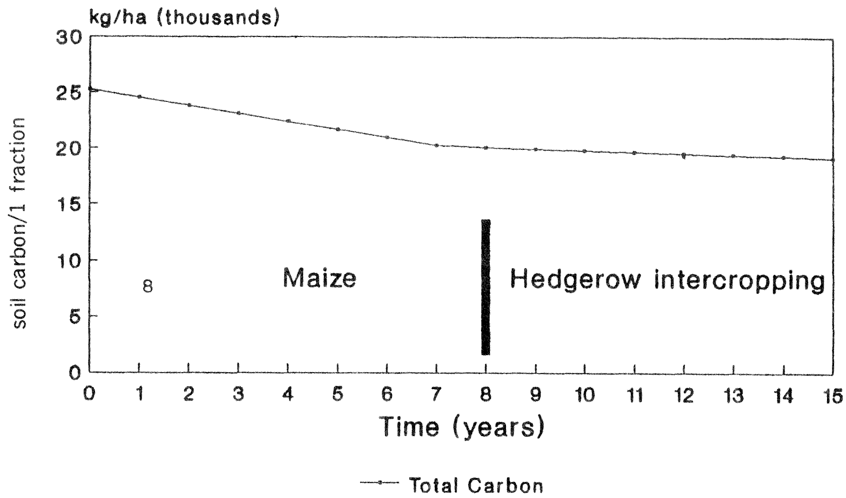


**Fig. 1 Example of output from the SCUAF computer model, showing changes in soil organic carbon under 8 years of maize monoculture followed by 8 years of hedgerow, intercropping ; lowland sub-humid climate, medium-textured soil, gentle slope.**

a sub-humid climate, medium-textured soil and gentle slope, without external inputs. Under continuous maize, soil organic matter declines ; other outputs (not illustrated) show a decrease in nitrogen availability and increase in erosion. Substitution of the hedgerow intercropping system checks soil degradation, leading to a system which is nearly sustainable -that is, soil fertility and plant growth are almost maintained at a constant level. SCUAF can be used to investigate the probable consequences of changing one or more values or treatments, for example, the effect on soil carbon of harvesting tree prunings instead of retaining them on the soil.

## An agenda for research

It should be made clear that many of the statements made above are at present supported only by scanty, although largely positive, experimental evidence. A substantial volume of agroforestry experimental work has been established over the last 5 years, from which results are only beginning to emerge. Given the very high apparent potential, however, further studies are highly desirable.

The general soil-agroforestry hypothesis (Sanchez, 1987 ; Young, 1989) is :

*Appropriate agroforestry systems have the potential to control erosion, maintain soil organic matter and physical properties, and promote efficient nutrient cycling.*

In a recent review, it is concluded that this hypothesis is essentially true, and applicable to a wide range of environmental conditions (Young, 1989a).

As an expansion of the above, ten specific soil-agroforestry hypotheses have been proposed (Table 4). Two additional mechanisms or sub-hypotheses have been proposed, as expansions of Hypothesis 4. These are that shading by a tree canopy improves the rate of mineralization of soil nitrogen (Wilson, 1990) ; and that where the roots of nitrogen-fixing trees ase in close contact with those of non-nitrogen-fixing plants, there is increased nodulation and direct transfer of nitrogen to the non-nodulating plant (van Noordwijk and Dommergues, 1990). An elaboration of Hypothesis 6, the synchrony hypothesis of the Tropical Soil Biology and Fertility program, has been noted above.

These ten soil-agroforestry hypotheses, together with the soils and climatic environments under which they are valid and the processes through which they operate, form an agenda for research.

## Conclusion

The potential benefits of agroforestry to sustainability, consisting of plant production coupled with resource conservation, are applicable both to low- and high-input land use systems. For low-input systems, which are dominant in most less-developed countries, agroforestry provides means of slowing the decline in soil fertility, so allowing cropping to continue for longer periods before fallowing or other means of fertility restoration become necessary. One such means is the technology of improved tree fallows, in which soil improvement at a rate faster than that under natural fallow is combined with plant production from the fallowed land. Agroforestry thus offers alternatives to shifting cultivation. For land use systems with moderate to high inputs, agroforestry increases the efficiency of nutrient cycling, thereby making better use of scarce resources.

The potential benefits of agroforestry to tropical agriculture are conditional upon two factors. First, the processes of soil improvement must be confirmed, and their efficiency improved, by substantial further research. Secondly, the various technologies of agroforestry must be widely adopted by farmers.

In the approach to research employed by the International Council for Research in Agroforestry (ICRAF), and the national research organizations with which it collaborates, these two factors are treated jointly. In the former approach to agricultural research, a technology was first developed scientifically, and only afterwards was the question of its acceptability to farmers considered. ICRAF's approach, embodied in the method of diagnosis and design (Raintree, 1987) is first to analyze not only the problems of land use systems but also the constraints to their improvement (e.g. lack of fertilizer, labour shortage at peak times). On-farm research is combined with on-station research from an early stage. Potential solutions to the problems are then designed, using only techniques which are known to be practicable and acceptable.

If the potential for sustainable plant production from agroforestry that is indicated by this review can be substantiated by further research, then the gains to the welfare of farmers in the tropics can become very high indeed.

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## Discussion

**Greenland, D.J. (UK)**: Trees may help increase available water storage in the soil but they also compete for water with crops. Can your model be extended to deal with water stress and relationships?

**Answer :** No. The SCUAF model at present covers changes in erosion, soil carbon and nitrogen, in other words nutrient cycling. We are aiming at extending it to cover phosphorus cycling. The treatment of tree/crop/soil water relations requires a short-term, i.e. 10 day period model (time with stochastic element model) for which SCUAF is not adapted. It is certainly desirable to develop a model to cover this important aspect.

**Khanna, S.S. (India)**: I would like to suggest that agroforestry systems are good for enhancing the prsoductivity of soil. I fully endorse your view that we should promote agroforestry particularly in India. However, whenever I talked to the farmers, they have mentioned the problem of birds attacking areas with a high density of trees near the fields. The damage caused by birds was particularly pronounced in arid areas where pearl millet is being cultivated as well as in fields with wheat and other crops.

**Answer :** I do not have an answer to this specific problem but I am glad that you raised an example of problem associated with agroforestry. There are many other problems and consequently there are dangers in our over-enthusiastic advocacy of agroforestry. To solve such problems we urgently need research so as to lead towards efficient design of agroforestry systems for specific conditions, environmental and socio-economic. May I also welcome your emphasis on the viewpoint of the farmer. ICRAF's approach to research, based on the method of diagnosis and design begins with an appraisal of the problems faced by farmers and the constraints on their solution. Continuing interchange with the farmers including on-farm research is an essential element in agroforestry research.