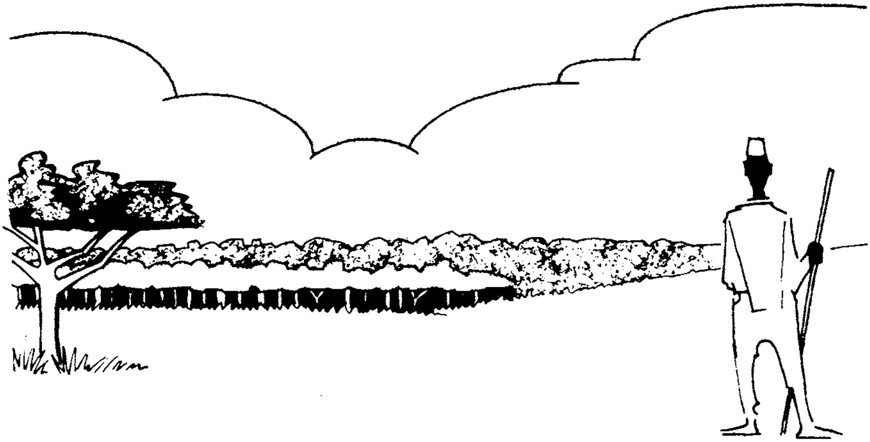
CHAPTER 2

TECHNICAL INPUTS TO ECONOMIC ANALYSIS



THE ROLE OF TREES IN MAINTAINING AND IMPROVING SOIL PRODUCTIVITY - A REVIEW OF THE LITERATURE

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INTRODUCTION

The role of trees in maintaining and improving soil productivity is considered central to the sustainability of many agroforestry systems. Do we know enough about the effects of trees on soils to quantify and value this role?

By reviewing some of the evidence for enhancement and maintenance of soil fertility by trees and by examining our current understanding of the mechanisms involved, we can start to consider how the benefits from trees might be evaluated in economic terms. The importance of selecting components of the system which might be used as parameters in the measurement of improved soil productivity is clear in this respect.

DEFINITION AND MEASUREMENT OF BENEFITS

Appropriate agroforestry systems, as well as many natural tree based ecosystems, are perceived to improve or maintain soil fertility and soil productivity, to promote soil conservation, reduce soil degradation and achieve sustainable production. These benefits are often attributed to the tree component of the system. Before examining the evidence it is necessary to understand what is meant by these concepts. Only through definition and understanding will it be possible to quantify and measure the beneficial effects of trees on soils.

Soil fertility can be simply defined as the capacity of the soil to support growth of plants. It is common therefore to consider it in terms of soil constraints to plant growth. Using nutrient content alone to indicate fertility is too restricted since crop nutrient responses are interactions between soil chemical constituents and the effects of soil condition on movement of nutrients and their uptake by plants. Soil chemical, physical and biological properties all contribute to soil fertility and should be equally considered in fertility assessment.

Despite our understanding of what contributes to soil fertility we generally limit its measurement to single soil properties such as % Base Saturation or more commonly to soil macro-nutrient

(NPK) status. The latter can be interpreted and valued in terms of crop fertiliser requirements. Soil nutrients data however can only point to excess or deficiency problems and only where correlation from crop trials have been established can fertiliser or management recommendations be usefully made.

Soil fertility is only one of a number of factors that determine the magnitude of crop yield.

Soil productivity is a broader concept relating to the ability of the soil to support crop growth on a sustained basis. It might be considered (and perhaps measured) as the soil's ability to maintain fertility over time. Crop yield, both amount and variability with time, can give some indication of the soil's productive capacity although productivity is not alone in determining crop yield response. Monitoring soil changes over time can be used to assess the maintenance of soil productivity. Land productivity includes soil productivity and all other land factors which influence crop growth.

Soil conservation in its broadest sense is the maintenance of soil physical, chemical and biological properties for which the prevention of soil loss by erosion is one condition. Erosion control can be measured as reduction in the rate of soil loss in units of tonnes/ha/year. With a knowledge of typical soil organic matter (SOM) and nutrient contents (kg/ha) of the topsoil which have been retained by conservation, some indication of conservation of fertility can also be made (Stocking 1986).

Degradation is defined as the 'results of one or more processes that lessen the current and potential capacity of a soil to produce, quantitatively and/or qualitatively, goods or services' (FAO 1977). It commonly arises from pressure of land use on resource. Recognised forms of degradation are erosion; acidification; lowering of nutrient content; biological degradation, which is linked to soil physical properties and nutrients; and physical degradation, which all lead to the lowering of soil fertility and productivity. It can be expressed by measuring changes in individual soil properties but is commonly reflected in decline of crop yields and reduced response to fertilisers.

Young (1987) distinguishes degraded soils which were once fertile and those which are inherently infertile, the former having more potential for improvement.

A **sustainable agricultural** system is one which can maintain productivity over a prolonged period of time without depleting renewable resources. Such systems are characteristed by high efficiency of internal resource use.

Yields, both in terms of amount and stability over time, can be used to indicate sustained productivity. The time scale might be considered in planning terms, Young (1987) suggests 20-50 years for farmers and planners, or over a longer time frame; for example Dumanski (1984) suggests sustainable production can be measured as 'average output over an infinitely long time period'. Sustainable systems are also believed to maintain stable yields in equilibrium with the environment, with little variation in response to typical environmental fluctuations. It is possible therefore to assess sustainability by measuring yield variation in response to environmental fluctuations over time.

Conservation of soil organic matter and efficient nutrient cycling are fundamental to sustainability of both natural and agricultural systems. Natural systems achieve this by internal regulation whereas agricultural systems are dominated by large inputs and outputs with little internal regulation. In addition to monitoring soil and yield changes over time to assess sustainability, we might also look to an understanding of the processes of internal regulation, by measuring nutrient storage and transfer and compiling budgets.

Clearly many variables need to be considered when assessing the fertility, productivity or sustainability of an agricultural system. Methods and units of measurement of such benefits need to be established before any attempt is made to evaluate the role of trees in agricultural systems in economic terms.

REVIEWS TO DATE

A number of reviews are available which provide a synthesis of the current information on soil productivity aspects of agroforestry and are valuable in highlighting gaps in research data (Mongi and Huxley (1979); Sanchez (1987); Nair (1984); Young (1987)).

These conclude that although the potential of trees for soil improvement is recognised, evidence from rigorous scientific studies of agroforestry systems by which trees affect soils is not yet complete. Attempts to understand the processes and to validate the concept of soil improvement are however now being made in soils research in agroforestry based on guidelines outlined in the above reviews (CSC, 1987).

EVIDENCE FOR THE IMPROVEMENT OF SOILS BY TREES

Many of the perceived benefits of trees in agroforestry systems are still hypothetical with much of the evidence observational or extrapolated from natural, plantation or annual cropping systems. Whilst much of the enthusiasm for agroforestry is for its value in marginal areas, the main documented work to date comes from areas of fertile, base-rich soils, specifically from two areas: experimental studies of hedgerow intercropping at IITA, Nigeria on pH6 Entisols and Alfisols, and from nutrient cycling work in cocoa and coffee plantations of Latin America on Alfisols and Andisols (Sanchez and et al 1985; Young 1987). Sanchez et al (1985) in their review, found little scientifically sound evidence that agroforestry systems improve soil properties in marginal areas and found it hard to adapt data from the above studies to acid base poor tropical Oxisols and Ultisols.

The evidence available to us in support of the proposition that trees improve soils comes from a number of sources, namely:

* Comparison of soils under natural tree based eco-systems and agricultural systems

* The effects of forest clearance on soils

* The restorative powers of fallow

* Observations of soil enrichment and improved crop growth under individual trees and shrubs

* Experimental agroforestry systems

* Reclamation of problem soils through afforestation

* Soils under plantations

Much of the evidence is indirect. For example, stable structures, good moisture holding capacity, resistance to erosion and good fertility with nutrients bound up in organic molecules of soils which have developed under natural woods or forests are often used to support the premise that trees improve soils. Similarly the deterioration of soil properties following forest clearance and their consequent improvement with bush fallow systems has often been used to demonstrate the benefits of trees. Studies on soil dynamics under shifting cultivation are numerous and evlauated by Nye and Greenland (1960); Sanchez (1976); Young (1976).

The success of reclamation forestry in improving fertility of some problem soils is used as further evidence for the value of tree cover. The potential ameliorating effect of trees on soils degraded by erosion and salinity in India is discussed by Tejwani, (1979); Gill and Abrol, (1986); Khanduja et al, (1986).

This discussion is restricted to reviewing the more direct evidence from some indigenous and experimental agroforestry systems.

THE EFFECTS OF INDIVIDUAL TREES AND SHRUBS ON SOILS AND CROPS BENEATH THEM

Introduction

Many tree species are valued by farmers and play an important role in traditional agroforestry systems. Some trees have conspicuous effects on crop growth beneath them and this phenomena has prompted studies to compare yields and soil properties under individual canopies with those outside the canopy. The following is a brief review of some of these studies and their results.

Acacia albida

This tree, which has the advantage of shedding its leaves at the start of the rainy season, is valued by farmers in semi-arid zones of W Africa and subhumid zones of Senegal, Malawi and Ethiopia. It has been the subject of a number of studies because of the apparent promotion of crop yield and soil fertility beneath its canopy.

Radwanski and Wickens (1970) quote Blair (1963) in his observation of irrigated wheat at Nyertete, Sudan - he recorded plants near *A. albida* trees of 80 cm height with 8 ears per plant, each with 32g rains compared to plants away from the tree which were only 30cm tall with 3 ears per plant and an average of 22 grains per ear.

Charreau and Vidal (1965) found the yield of *Pennisetum* millet growing near *A. albida* 2.5 times more than the yield away from the tree and the protein yield of the crop 3.5 times greater than outside. This yield increase correlated with a several fold increase in soil nitrogen and organic matter. Soil water holding capacity and structure under trees were also improved compared to outside.

Felker (1978) in his review concluded that, in the infertile sandy soils of the peanut basins in Senegal, yields of peanuts and millet increase from 500 ± 200 kg/ha under *A. albida* foliage (Dancette and Poulain 1969; Charreau and Vidal 1965).

Young (1987) comments that yield increases are reported to be more pronounced under conditions of low fertility.

Radwanski and Wickens (1967) compared soil profiles under *A. albida* and under *Balanites aegyptiaca* on the mantle soils of lower pediments in Zalingei, Sudan. These gravelly soils have a small clay content, low water holding capacity, little structural stability when wet, and low resistance to erosion. *A. albida* was observed to modify these adverse physical soil conditions with more organic matter (shown by darker and thicker surface layer) and more stable structural aggregates found in soil under canopies. They suggested that improved moisture conditions under *A. albida* (8%) compared to *B. aegyptiaca* (4%) (measured just before the rainy season) were partially the result of these improved physical conditions and reduced evaporation, although *A. albida* naturally occurred on moister soils than *B aegyptiaca*. (Schoch (1966) explained reduction in potential evapotranspiration under *A. albida* as due to full leaf canopy in the dry season).

Contents of organic carbon, nitrogen and phosphorus differed significantly between the two soils with the uppermost horizon of *A. albida* profiles containing more carbon, nitrogen and phosphorus but less potassium (Table 1)

Table 1 Comparison of Soil Nutrient Content under and outside *Acacia albida* Canopies (after Radwanski and Wickens, 1967)

Profile	Under *A. albida*			No *A. albida*		
	1	2	3	4	5	6
Organic carbon (%)	0.78	1.43	1.78	0.76	0.42	0.81
Total nitrogen (%)	0.15	0.39	0.73	0.07	0.05	0.08
Total phosphorus (mg/100 g)	35.0	35.0	35.0	26.0	20.0	23.0
Total potassium (mg/100 g)	164.0	252.0	172.0	300.0	220.0	284.0

Bernhard-Reversat (1982) comparing soils under *A. albida*, *B aegyptiaca* and *Adansonia digitata* with those outside the canopies on sandy lithosols in semi-arid N Senegal, found a gradient in SOM (Soil Organic Matter) and total nitogen away from the trees, decreasing both with depth and distance from the trunk.

Prosopis

This genus (43 species) is considered to have great potential for soil improvement in semi-arid and arid zones.

In Indian arid zones there is a long tradition of growing pearl millet *(Pennisetum glaucum)* under *P. cineraria* (Khejri) which supports better growth of this crop as well as a large number of forage species (Mann and Saxena 1980). Farmers in W Rajasthan are reported to maintain *P. cineraria* trees in densities as high as 150 trees/ha in pearl millet fields (Radwanski and Wickens 1981). Soil studies show an increase in SOM, nitrogen content, Zn, Mn, Cu and higher moisture availability in the surface layers under *P. cineraria* compared to open fields or *P. juliflora* (Aggarwal 1980) (Table 2).

Table 2 Soil nutrient content beneath Prosopis spp.. North-west India (Aggarwal, 1980).

	Depth (cm)	Available nutrients (kg/ha) N	P	K
Prosopis cineraria	0-15	250	22.4	633
Prosopis juliflora	-	250	10.3	409
Open field	-	203	7.7	370
Prosopis cineraria	15-30	193	10.3	325
Prosopis juliflora	-	212	4.5	258
Open field	-	196	4.0	235

A considerable amount of work has been carried out on *Prosopis* shrubs, (mesquite) in USA deserts to investigate the effects on soils and and vegetation beneath. Tiedemann and Khemmedson (1973) found herbage yield was four times greater in growth chambers using soil from beneath *Prosopis* shrubs in Arizona compared to the open grown control.

Felker (1981) quotes figures for nitrate content of soil saturation extract under *P. glandulosa* var. torreyana in Californian desert for a 30cm sample of 400 mg/kg under the tree compared to 100 mg/kg away from the tree. This 1200 kg nitrate/ha is only possible because of low rains eliminating leaching loss.

Barth and Klemmedson (1978) tried to characterise spatial patterns of soil and plant dry matter, nitrogen, organic carbon and pH as influenced by velvet mesquite and blue palo verde (*Cercidium floridum Benth*) in the Arizona desert. The weight of under storey vegetation and shrub litter declined with distance from the shrub centre for all shrubs, while soil nitrogen and organic carbon declined from the shrub centre with distance from canopy and with soil depth. These shrub - induced horizontal gradients were most obvious in surface soils with surface nitrogen declining by 50% from tree bole to outside, and surface C by 50-60%.

Other examples of microsite enrichment under tree/shrub canopies.

Soil samples from under 3 dominant shrubs, *Acacia gregii* (legume), *Cassia armata* (legume) and *Lannea divaricata*, of a desert wash plant community on gravelly sand loams showed a decrease in nitrogen with depth and lateral distance from shrub centres (Garcia-Moya and Mckell 1970).

Kellman (1979) found that 5 broadleaf species native to neotropical savanna in the subhumid zone of Belize preferentially enriched the soil around them. Mineral nutrient (N, P, K, Ca) enrichment was essentially superficial, rising from low levels in the open to high levels under trees where levels were equal or sometimes greater than nearby rainforest soils.

In miombo woodland in Zimbabwe, Campbell et al (1988) found that soil properties were related to proximity to the tree trunk. In areas of closed woodland, organic matter, extractable P and nitrate N were significantly higher in soils at the base of tree trunks compared to a few metres away.

There are many other examples of trees valued as soils or crop improvers which are part of the farmed landscape. For example, in Natural Regions III–IV (m.a.r 400–800mm) in Zimbabwe, *Parinari curatellifolia*, *Ficus sur* and *Ficus sycamorus* are retained in arable fields primarily for fruit and shade. Maize growth beneath these tree canopies is often observed to be enhanced, particularly in drier seasons. Preliminary investigations suggest that position under the canopy does influence maize cob size for all species with the highest volumes obtained at midcanopy and edge positions. Farmers recognise the benefits of the trees on yields and often reduce fertiliser application under the canopies (Abel et al 1988).

Gerakis and Tsangarakis (1970) looked at the influence of *A. senegal* fallow on soil fertility and crops in central Sudan. Trial results for sorghum on Goz sands show that first year yields after 12 year fallow are better on soils where *A. senegal* trees had been uprooted than away from them. Soil samples taken in radii away from uprooted tree centres showed increases in *nitrogen* (at 0–20cm) and organic C which was higher for all soil layers but particularly the top. No difference however, in pH, available phosphorus, exchangeable potassium or texture were detected.

Radwanski (1969) working in Nigeria, compared Neem (*Azadirachta indica)* fallow with abandoned farmland fallow on red, acid 'problem' soils which are leached, have little organic matter and no structural aggregation. This soil has even been observed to deteriorate with the natural regenerative fallow employed in shifting cultivation because erosion occurs before a ground cover is established.

Results from the study are presented for 0–7.5cm composite soil samples (Table 3). pH, organic carbon and total nitrogen were all greater under Neem but phosphorus was greater under fallow. Total cations, Base Saturation and CEC are all considerably higher under the Neem fallow. Sampling was in the dry season and the farmland soil was dry throughout although lower horizons of Neem soil were reported to be still moist.

Table 3 A Comparison of Soil Properties in Nigeria under Neem Fallow as Compared with Abandoned Farmland Fallow

	Abandoned Farmland	Neem fallow
pH	5.4	6.8
C%	0.12%	0.57%
Total N%	0.013	0.047
CEC(me/100g soil)	1.70	2.25
%Base Saturation	20%	98%
Total cations(me/100g soil)	0.39	2.40
Avail P(ppm)	195	68

Interpretation of all the above evidence must be treated with some caution. All these studies assume that soils inside and outside tree/shrub canopies were initially the same and that any differences now observed could be explained in terms of the effect of the tree. It may however be differing conditions in the soil to start with which explain tree establishment and distribution. For instance in the Jebel Marra Highlands of Sudan, *A. albida* dominates on ash soils with relatively high nutrient reserves, CEC and Base Saturation (Miehe 1986). Similarly increased clay contents reported beneath *A. albida* (Jung 1966) and *P. cineraria* (Mann and Saxena 1980) may explain the trees' presence, rather than be a result of the tree. The need for well designed studies and soil characterisation when investigating the effects of trees on soil is clear.

AGROFORESTRY SYSTEMS RESEARCH

Young (1987), Nair (1984) and Sanchez (1987) have reviewed results from agroforestry systems research in raltion to soil productivity, and species which have potential as soil improvers within agroforestry systems have been proposed (Young 1987; Nair 1984). One alley cropping study, which monitors soil changes with time, is that of *Leucaena* intercropped with a maize-cowpea rotation (annual) on sandy soil at Ibadan (Kang et al 1981; 1985). Table 4 shows soil condition, before and after hedgerow intercropping and compares the effects of retaining or removing prunings. The application of prunings led to higher SOM, potassium, calcium and magnesium and improved AWC, but there was no change in phosphorus. SOM was maintained over the six years compared to a decline when prunings were removed.

Table 4 Soil changes under hedgerow intercropping with *Leucaena*, Ibadan, Nigeria. Values are for unfertilized plots, soil depth 0–15cm. Source: Kang et al (1981, 1985).

Treatment	pH	Org.C	Exchangeable (meg/100g) K	Ca	Mg	Bray P ppm
Before H.I	6.2	0.98	0.25	2.63	1.02	25
After 3 yr H.I, prunings removed	5.7	0.96	0.16	5.07	0.35	19
After 6 yr H.I, prunings removed	6.0	0.65	0.19	2.90	0.35	27
After 3 yr H.I, prunings retained	5.7	1.47	0.16	5.33	0.43	22
After 6 yr H.I, prunings retained	6.0	1.07	0.28	3.45	0.50	26

The following is a selection of some of the evidence available from various land use systems. The potential of trees as soil improvers is apprarent but clearly more quantitative evidence from research in agroforestry systems in required. Work on soil dynamics under tree plantations suggests that a decline in soil fertility can result (Lundgren 1978) and it is important to remember that trees have adverse effects on soils as well as beneficial ones. The value of well designed experiments and full characterisation of soils is obvious.

PROCESSES BY WHICH TREES AFFECT SOILS

The evidence for soil improvement under trees can be summarised as follows:

* Increase in SOM (% organic carbon)
* Increase in nutrients (predominantly total nitrogen and exchangeable bases)
* Improved physical structure (more stable aggregates, increased AWC, reduced bulk density, improved infiltration)
* Reduced erosion and runoff (tonnes/ha/year)
* Improved moisture status (% moisture content, improved AWC)
* Crop improvement (yield kg/ha, height, ears per plant, grains per ear, protein content)

The available evidence allows us to postualte how these changes might be brought about. The following discussion concentrates on the role of the tree and the mechanisms by which it affects the soil rather than the converse. It is not possible to consider fully the processes whereby crop growth is enhanced under trees since microclimatic effects are beyond the scope of this review.

Processes can be discussed under the following headings:

* Protection
* Conservation and increase of SOM
* Increase in nutrient status
* Nutrient cycling
* Improved moisture status

Protection

Protection of soil against erosion, runoff and compaction is considered one of the principle roles of trees. Both canopy and litter can protect the surface from the impact of erosive rains and dampen extreme moisture/temperature fluxes. The effectiveness of different tree covers varies. It is generally considered that tree canopies in communities of bush fallow with different strata are more effective than artificial fallow or monoculture plantation crops, although runoff and erosion recorded from soil under plantation crops can be comparable to that under natural forest (Sanchez et al 1985).

Litter has been shown to be of more value than canopy cover. In a study of an *A. auriculiformis* plantation in Java the effects of tree canopy removal, undergrowth and litter on soil erosion were compared. While the canopy alone had little effect on soil erosion, and the undergrowth effect was small, litter reduced erosion by 95% compared to bare ground (Wiersum 1985). Mulch used in cropping or agroforestry systems plays a similar protection role.

It is questionable that trees are any more efficient at protection than annual crops which can cover soil far quicker. When mulched or managed with low tillage annual crops give the same results for soil loss as do secondary forests (Lal 1977). Trees can take more than two years to close canopy in humid tropics during which time the ground is bare, as litter is still insufficient to cover it. This contrasts with annual crops which can provide adequate cover within 30–45 days and pastures within 2–6 months (Sanchez 1987).

Trees and shrubs can also protect the soil against wind erosion by retarding the movement of soil particles, as observed in deserts (Garcia-Moya and McKell 1970). Capture of clay particles during dust storms might also explain the higher proportions of clay found under *A. albida* and *P. cineraria* canopies (Jung, 1966; Mann and Saxena, 1980). Tree roots are also valuable in anchoring unconsolidated soils. Another aspect of protection that is afforded by a ground cover of litter (or mulch) is a reduction in temperature and moisture flux.

Conservation and Increase of Soil Organic Matter (SOM)

The increased supply of litter (above and below ground residues) in tree based systems is considered responsible for maintenance or increase of SOM. SOM is a major component in the plant-soil nutrient cycling system, and its maintenance or increase is fundamental to many soil improving processes. In addition to the increased supply of residues to the soil there may also be a coincident increase in the rate of humus mineralisation due to reduced cultivation and lower temperatures under trees.

(i) Sources of organic matter

The two main sources of litter are below ground (roots) and above ground (leaves, branches, twigs, fruit).

a) Below ground biomass and litter

Roots make a constant contribution to SOM through decay. They can represent 20-25% of the total living biomass of trees (Armson 1977) although this proportion will vary in different environments. Roots are thought to make a relatively small contribution to tropical forest systems where many of them are concentrated at the surface whereas in semi-arid and arid regions the proportion is greater. For example, at the end of the fallow period at sites in Sri Lanka and Sarawak, root biomass was 17% and 13% of total biomass respectively (Andriesse 1987); whereas roots of *Acacia gregii* and *Cassia armata* in desert wash plant community were found to be 55% and 41% of dry weight of the plant respectively (Garcia-Moya and McKell 1970). In moist savanna areas typical figures are 35-40% total plant biomass (Young 1987).

Table 5 shows root biomass for a range of land use systems compared to leaf biomass (Ewel 1982).

Table 5 Leaf and Root Biomass in Nine Land Use Systems (Ewel 1982)

	Agricultural systems			Forest Systems		Agroforestry Systems			
	Young maize	Mature maize	Sweet potato	Gmelina plantation	Secondary forest	Coffee-Erythrina	Cacao-Cordia	Tree garden	Planted fallow
Leaf biomass, kg/ha	300	1000	1070	3120	3070	2720	2040	2450	2480
Root biomass, kg/ha (to 25cm)	390	1150	410	1280	2170	2350	2720	3070	4220
Ratio, roots to leaves	1.18	1.15	0.38	0.41	0.71	0.86	1.33	1.25	1.70

These are estimates of root proportions at any one time but turnover of feeder roots by sloughing off, rapid decay and exudation can increase the contribution of roots to SOM substantially. In addition it is suggested that there is formation of SOM directly from root tissue without intervention of soil microfauna. Martin (1977) suggests that a steady release of carbohydrate-rich organic material from actively growing roots represents a high energy input into soil ecosystems capable of supporting a substantial microbial population.

Unlike above ground biomass, root residues are rarely removed from the soil and therefore play a central role in SOM maintenance. Root residues are particularly important in shifting cultivation systems where above ground material is lost in burning.

b) Above ground biomass and litter

There have been many estimates of total above ground biomass and its distribution amongst the different components of natural forest ecosystems. Nair (1984), Young (1987) and Sanchez (1979) present summaries of this material.

The potential contribution of organic matter addition that can be expected from an ecosystem according to climatic zone is indicated in the following summary of figures for net primary production of above ground dry matter.

Humid tropics (no dry season): 20 000 or more kg/ha/yr
Humid tropics (short dry season): 20 000 kg/ha/yr
Subhumid tropics: moist 10 000 kg/ha/yr
Subhumid tropics: dry 5 000 kg/ha/yr
Semi-arid zones: 2 500 kg/ha/yr (Young 1987)

Table 6 present figures for biomass of different components of fresh vegetation at the end of the fallow period in Sri Lanka and Sarawak. The critical factor, however, is which of these components will reach the soil as litter. In this respect it is interesting to note that leaf biomass is only 8.8% and 9.9% of total above gound biomass in Sri Lanka and Sarawak respectively.

Litterfall is the major recognised pathway of organic matter addition to the soil. Figures for rates of litterfall are available from a number of studies and summarised in Table 7. The amount of litter in the system at any one time is also an indication of the contribution from litter fall. Andriesse (1987) sampled litter in the dry season in Sri Lanka and during the least wet part of the year in Sarawak. The former amounted to 3 360 kg/ha compared to 9 800 kg/ha in the latter. It was felt that the large amount in Sarawak was a reflection of the high biomass regeneration and turnover.

Table 6 Oven-dry weights in kg/ha and as % of total living above-round biomass at Sri Lanka and Sarawak (Andriesse 1987)

	trunk	small wood	twigs	leaves	fruit	total
Sri Lanka						
tree	24600	11000	6000	2400		44000
bush	10000	7000	5000	2000		24000
shrubs	-	5000	5000	2000		12000
herbs	-		500	500		1000
Total	34600	23000	16500	6900		81000
% of total	42.7	28.4	20.4	20.3		
Sarawak						
trees and shrubs	21606	4589	1945	2079	28	30247
lianas	-	431	194	70		695
ferns and grasses	-		159	1027		1186
Total	21606	5020	2298	3176	28	32128
% of total	67.2	15.6	7.2	9.9		

Biomass production from tree components in agroforestry systems can approach that of natural vegetation systems. In one alley cropping system at Ibadan (moist subhumid/humid), total biomass production of the system reached some 15 000 kg/ha/yr when the crop net primary production of about 10 000kg/ha/yr from two crops was added (Young 1987). The *Cordia-Erythrina* component in coffee or cocoa plantations in Central and South America can typically supply some 10 000 kg/ha/yr above ground biomass (Young 1987).

Table 7 Rate of Litter Production (per annum) (Nye and Greenland, 1960)

Vegetation	Place	Little fall(kg/ha)	Nutrients in litter (kg/ha) N	P	K	Ca	Mg	Authority
Forest (Namanja dominant)	Congo	14800 (dry matter)	139	4.6	103	127	38	Laudelout (1985)
Mixed forest	"	12500 (dry matter)	228	6.8	48	105	46	"
Mixed high forest	Ghana	10720 (oven dry)	203	7.3	64	205	40	Nye (Unpublished)
Rain forest	Colombia	10500 (oven dry)						Jenny (1950)
" "	"	10600 (oven dry)						"
" " (Sub-tropical mixed app.)	Queensland	6000 (oven dry-leaf only)	107	6.8	34	75		Webb (1956)
Temperate	New York	3100 (dry matter)	18	3.3	15	74		Chandler (1941)

Typical leaf yield values (dry weight) for alley cropping shrubs at IITA are presented below (Table 8).

Table 8 Leaf yields from leguminous woody shrubs at IITA, Ibadan, Nigeria

Shrubs	Leaf yield dry weight kg/ha/yr
Gliricidia sepium	2300
Tephrosia candida	3067
Cajanus cajan	4100
Leucaena leucocephala	5000 - 8000

Source: Kang et al (1981); Wilson and Kang (1981)

Young (1987), considering only topsoil carbon and assuming it all belongs to the labile fraction (half life of about 3 years in tropical soils) estimated the amounts of plant residues needed to be added to the soil to maintain SOM. Results suggest that to maintain SOM the in the humid tropics, 8 000 kg dry matter above ground residues ha/yr are needed to return to the soil while 4000 kg and 2000 kg are required for subhumid and semi-arid areas respectively. Comparing these figures with those available for biomass production from agroforestry systems, he concluded that SOM can be maintained only if total tree biomass is added to the soil. If woody material or foliage is harvested, a deficit results. In considering the amount of biomass needed to maintain SOM it is important to distinguish between the different tree components (litter, roots, wood, fruit) which might reach the soil or might be removed in harvest.

This represents a method for assessing the potential of different systems and component species to conserve SOM and therefore allow some quantification of requirements for a sustainable system.

(ii) **The value of SOM**

The build up of SOM is associated with both chemical and physical changes which are intimately linked. The following are the recognised benefits of SOM conservation or improvement:

a. improved/maintained soil physical properties
b. improved ion exchange material
c. improved substrate for microbes
d. improved source of inorganic nutrients
e. moderating effect on extreme soil reactions.

SOM is not a homogeneous material. Recent work using isotope labelling has enabled the identification of at least 3 pools or fractions which are distinguished by their turnover rates in soil. For example, Parton et al (1963) define three such functional pools:

Active SOM	- turnover 0-3 years
Slow SOM	- turnover up to 25 years
Passive SOM	- about 1000 years

Most of the immediate source of nutrients comes from the active pool but the slow and passive pools are equally important in promoting soil structure and providing a source of slow-release nutrients. What is clear is that SOM is one of the most important of soil properties but is also the least measurable because of our limited understanding of these functional pools. Analysis for % organic carbon in soil gives an estimate of total SOM, whereas methods of separating microbial, light and heavy fractions are necessary to determine the extent and the dynamics of the functional pools under trees or agroforestry systems.

a. Improvement or maintenance of soil physical properties

The physical properties of soil depend on the degree of aggregation between particles and the volume and size distribution of pores which determine available water holding capacity and root penetration.

Although these are influenced primarily by texture and clay type, organic gums and fungal mycelia can bring soil particles into aggregates resulting in structural stability and good pore size distribution, which in turn provides good water holding capacity, favourable permeability and aeration, a good rooting environment and resistance to surface erosion. The value of SOM in this role is evident when loss of SOM brings about capping, compaction and surface crusting and pan formation.

The importance of physical structure cannot be overlooked. Available nutrients may be useless if soil properties do not favour proper root development to tap them. Declining yields during cropping periods of shifting cultivation sometimes cannot be revived by fertiliser application alone (Ahn 1979). Some tropical soils however are not so easy to degrade, due to stable microaggregation and the value of organic matter to these is less (Ahn 1974).

Sanchez et al (1985) note the importance of tree roots in promoting good structure in soils beneath plantations by loosening topsoil by radial growth - improving subsoil porosity when roots decay.

b. Ion exchange material

Cation exchange capacity (CEC) is known to be enhanced by the clay-humus complex in soil. Raising humus levels, where clay minerals have low CEC, such as kaolinite, can be particularly valuable. Higher CEC results in improved nutrient retention and enables a greater efficiency of nutrient utilisation.

Juo and Lal (1977) compared *Leucaena* and bush fallows on Alfisols in W Nigeria. After 3 years CEC was significantly higher in the soil receiving *Leucaena* prunings compared to the bush fallow.

c. Substrate for microbes

Improvement of SOM status can result in an increase in activity of favourable microorganisms in the root zone. Such microorganisms can contribute to nutrient release and may also produce growth promoting substances.

Jung (1966, 1967) compared microbial changes under and away from *A. albida* and found an increase in invertase, dehydrogenase, asparaginase and respiratory CO_2 under the canopy. Bacteria counts were the same at the two sites but there was a marked increase in fungi and actinomycete population under *A. albida* which he took as an indication that the soil would be able to degrade leaf litter and release nutrients more quickly. However, slow decomposition of surface litter/mulch is associated with no till systems and this has been related to a higher proportion of fungi (Holland and Coleman 1987).

It has also been suggested that good SOM status provides a favourable soil environment for nitrogen fixation.

d. SOM as a nutrient source

The decomposition of raw organic residues and the mineralisation of SOM will result in nutrient release. Young (1987) recognises the following favourable aspects of SOM as a nutrient source:

- supply is balanced across the range of primary, secondary and micronutrients

- nutrients in the form of organic molecules are protected from leaching

- there is a slow release of nutrients in an available form through mineralisation

In addition, there will be a blocking of phosporous fixation sites by organic complexes, and complexing results in improved availability of micronutrients.

Above ground litter

Amounts of nutrients returned in the soil litter can be estimated with a knowledge of typical nutrient contents of tree components and the extent to which they contribute to litterfall.

For fallow sites in Sri Lanka and Sarawak, Andriesse (1987) found that leaves contain the highest amounts of all nutrient elements (being notably high in nitrogen and potassium) except sometimes calcium which is higher in bark; and that the relative nutrient accumulation is found in the sequence trunks < branches < leaves. He also found the high calcium values of litter in Sri Lanka were reflected in the calcium levels found in the living vegetation.

Table 7 summarises data for amounts of nutrients added to soil in litter for a range of forest systems. Table 9 presents the total macronutrients stored in the litter at the Sri Lanka and Sarawak sites.

Table 9 Total of major nutrients stored in litter for Sri Lanka and Sarawak sites in kg/ha; oven-dry basis (Andriesse 1987)

	N	P	K	Ca	Mg	Total Litter
Sri Lanka	38	1	10	71	7	3.360 kg/ha
Sarawak	137	4	20	152	19	9.800 kg/ha

Similar estimates can be made for agroforestry systems. *Erythrina, Inga* and *Cordia* which are combined with cocoa and coffee in Latin America, produce large amounts of biomass and there is a large potential to contribute significant amounts of nutrients to the soil (Table 10).

Large nitrogen returns can be explained partly by nitrogen fixation however non-N-fixers can still contribute substantial amounts of nitrogen.

Juo and Lal (1977) in comparison of *leucaena* and bush fallow found that the *Leucaena* plot receiving prunings for 3 years had a significant increase of calcium and potassium compared to the bush fallow. Kang et al (1985) found higher nutrient status in a plot (pH6 Entisol) receiving *Leucaena* prunings for 6 years compared to that receiving no prunings (Table 4).

Table 10 Return of nutrients to soil in litter and prunings for some agroforestry species.

		N	P	K	Ca
		(kg/ha/yr)			
Glover and Beer (1986) (Fertilised)	Coffee	148	8	88	87
	Trees	183	14	74	241
Russo and Budowski (1986)	*Erythrina poeppigiana*	330	32	156	319
Yamoah et al (1986)	*Gliricidia sepium*	238	14	152	
	Flemingia congesta	78	8	57	
	Cassia siamea	186	20	100	
Keerakoon and Gunasekera	Leucaera *leucocephala*	105	5	37	

After Young (1987)

It should be noted that whatever the potential of litter/prunings, large amounts of biomass may be needed to achieve sufficient nutrient returns.

Below ground litter

Below ground litter represents another major source of SOM and therefore a potential source of nutrients. There is little data available for nutrient content of root residues or on rates of addition of residues to the soil, but, given the amount of root mass in proportion to the total plant the contribution of nutrients from this source should not be ignored.

Nutrients in the root system at the end of the fallow period in Sri Lanka and Sarawak are given in Table 11 (Koopmans and Andriesse 1982):

Table 11 % of plant biomass nutrients in root system

	N	P	K	Ca
Sri Lanka	16	9	13	17
Sarawak	13	28	18	12

For nitrogen-fixing perennials, roots may be expected to be the main source of nitrogen however the distribution of fixed nitrogen within the plant will depend on a number of factors including species, stage of development etc. Studies with mature cowpea found only 5-6% nitrogen in roots and nodules (Minchin et al 1978). Figures for nitrogen content of perennial legume leaves suggest that nitrogen is translocated in large amounts to leaves although Andriesse (1987) found that leguminous plants were effective at storing nitrogen in all tree components. Nitrogen-fixing roots however can still contribute nitrogen by decay and slough of nodules, decay upon plant senescence and perhaps by nitrogen excretion from nodules as demonstrated by Eaglesham et al (1981) for annual nitrogen fixes.

Garcia-Moya and Mckell (1970) found nitrogen content of soil under non-leguminous desert shrubs followed the pattern of root distribution with contrasting patterns of root growth giving rise to different patterns of soil fertility. Barth and Klemmedson (1978) noted abundance of roots near non-nodulating shrub centres in USA desert and near the surface which coincided with patterns of soil nitrogen and carbon.

Factors affecting SOM decomposition and mineralisation

We have established that large amounts of litter/prunings can be returned to the soil in both natural and agroforestry systems and that these can contain substantial amounts of nutrients.

It is the process of decomposition however that regulates the rate of nutrient supply from these residues and the process of mineralisation which determines the rate of nutrient release from SOM. In simple terms, the rate of decompostion is a function of resource quality of the litter (C:N, lignin content etc) and of soil environmental conditions (temperature and moisture). Factors influencing mineralisation, although less understood, are believed to be the same.

The range of litter qualities from tree-based ecosystems (wood, leaf, twig, root, fruit) have different decomposition rates and this helps to distribute the release of nutrients over time.

Barth and Klemmedson (1978) proposed that differences in C:N suggest a more favourable decompostion environment under mesquite canopy than beyond. Similarly Radwanski and Wickens (1967) found a low C:N ratio under canopy of *A. albida* and suggested that SOM composition was such that available nitrogen could readily be released to the sorghum crop.

The soil environment, particularly moisture, influences the microbial activity, and therefore the rate of decomposition and mineralisation. In seasonal climates, decomposition and mineralisation of litter is also seasonal, with decomposition halting or slowing down in the dry season. This has been demonstrated in miombo woodland in Zimbabwe where nitrification rates show a strong correlation with soil moisture and marked seasonality (Swift and Hatton, unpublished).

Radwanski and Wickens (1967); Charreau and Vidal (1965); Jung (1966; 1967) and Dugain (1960) all attribute increase in crop yield under *A. albida* to the fact that leaf litter is provided at the start of the rainy season when it can be readily and rapidly be decomposed allowing crops to benefit from increased available nutrients.

Bernhard-Reversat (1982) observed two peaks of nitrogen mineralisation in semi-arid savanna of Senegal which were related to rainfall distribution. Mineralisation occurred mainly at the beginning of the rainy season and was shown to be a function of the number of days in which the soil was wet, for a given temperature and nitrogen content.

With a knowledge of factors that influence decomposition rates such as litter quality and soil moisture, it is possible within agroforestry systems to manipulate them by management, with the aim of synchronising release of nutrients with periods of crop nutrient demand. There is also potential for managing organic matter as a nutrient store. The value of nitrogen being held in organic form in SOM or immobilised by microbial biomass is that it is protected from loss from the system by leaching.

Increase in nutrient status

Trees have the ability to augment the nutrient status of soils by various mechanisms. Most important is the potential for some trees to nodulate and fix atmospheric nitrogen.

i) **Nitrogen fixation**

The role and potential of woody perennial legumes as N-fixers in agroforestry is well documented. Allen and Allen (1961) estiamte that about 1000 species of woody legumes form nitrogen fixing nodules. The ability to nodulate, however is not universal to all members of the legume family. The *Caesalpinoideae* subfamily nodulate less frequently than *Mimosoideae* and *Papilionoideae.* In addition, a few non legumes such as the genus *Casuarina* can fix N.

The amount of nitrogen fixed will depend on cultivar, species, number of nodules, their size, longevity and bacterial strain, the conditions of growth and management of the crop, soil available water and soil nutrient status and reaction. Amounts of fixed-nitrogen recorded for agroforestry tree species are reported by Dommergues 1987; Nair 1984 and Young 1987. These can range from 500kg/ha/yr for *Leucaena* to 21kg/ha/yr for *A. albida* (Felker 1978).

It is difficult to predict both the ability to nodulate and the amount of nitrogen fixed as this depends on many environmental factors as well as plant characteristics.

Habish (1970) in his work with *acacias* found 15% soil moisture, pH 6.5–7.0 and soil temperatures up to 35½C as optimum for growth and nodulation. All *acacias* he studied nodulated effectively at 7.5% soil moisture which was equivalent to 30% of water holding capacity of the sandy soil he used. Dry season low moisture in arid soils might explain the relatively poor nodulation on roots of *A. albida* and *B. aegyptica* reported by Radwanski and Wickens (1967) in Sudan, where soils had 8% and 4% soil moisture respectively.

Nodulation is greater in conditions of low soil nutrient status, whilst nitrogen fertilisers are known to inhibit nodulation. The phenomenon of more pronounced yield increase under *A. albida* canopies in low fertility conditions might therefore be attributed to greater N-fixation. However an increase in nodule biomass and function in *Inga jinicuil* was found to correlate positively with increasing phosphorus applications to coffee (Young 1987).

For many legume trees field evidence for nitrogen fixation is still confused. Some workers report nodulation and nitrogen fixation on roots of *Prosopis* and *Acacia* (Habish and Khain 1970; Felker et al 1980). Felker (1978) proposed that the increases in nitrogen and crop yields under *A. albida* were due to nitrogen fixation and estimated that 21 kg N/ha/yr was fixed, although generally few nodules are observed. Gerakis and Tsangerakis (1970) similarly attribute higher fertility under *A. senegal* in Sudan to nitrogen fixation.

Evidence available for *Prosopis* suggests that although they can nodulate they may not do so under extreme environmental conditions, and that even when nodulated, active nitrogen fixation occurs only when water is available (Sprent 1986).

Jung (1967) concluded that although nitrogen fixation is possible in *A. albida* it is not essential as these trees create a good nitrogen regime through normal microbial processes. Garcia-Moya and Mckell (1970) found no difference in the amounts of vegetation and soil nitrogen between legumes and non-legumes in a desert wash plant community, and concluded that the importance of the shrubs was more as a reservoir rather than for nitrogen fixing. Bath and Klemmedson (1978) found no evidence of nodulation in legume shrubs in Arizona.

Non symbiotic nitrogen fixation

Free living nitrogen fixing bacteria are known to be heterotrophic and therefore dependent on organic C for energy. It is possible that an increase in organic C can create a favourable environment for proliferation of these bacteria and explain the nitrogen rise around non nitrogen fixing plants such as Neem (Radwanski and Wickens 1981).

It is clear that nitrogen fixation offers great potential for augmenting the nitrogen status of soils. It is important however to be aware of the environmental and plant limitations to nodulation and nitrogen fixation.

ii) **Atmospheric deposition**

Atmospheric deposition of nutrients dissolved in rain or contained in dust represents another mechanism whereby trees can capture nutrients.

Kellman (1979) could not explain enrichment of soils under common savanna trees and shrubs on Ultisols in Belize by increased CEC under canopies or by deep rooting. He proposed that atmospheric deposition in rain was a major source of nutrients and that there was a gradual accumulation of mineral nutrients over time by perennials.

Andriesse (1987) suggested that atmospheric inputs or deep groundwater inputs by brackish water might explain high levels of Ca and Mg in vegetative components in Sri Lanka where soils were inherently infertile. Table 12 shows amounts of nutrients added to soil in rainfall compared to litter for a plantation in Brazil.

Table 12 Nutrient inputs and outputs in a high-yielding 17-year-old cacao plantation, shaded by *Erythrina fusca*, on a fertile Typic Tropadalf in Itabuna, Brazil (mean of 2 years) (Calculated from Santana & Cabala-Rosand 1984)

		Input or Output ($kg ha^{-1} yr^{-1}$) of N	P	K	Ca	Mg
Inputs	Rainfall	23	3	21	18	12
	Litter	112	13	25	162	53
Outputs	Harvest 1 t ha^{-1} of beans +1 t ha^{-1} of pods	44	10	20	1	3
	Leaching	68	0.5	2	38	63
Balance		+ 23	+ 6	+24	+141	-1

The extent of the contribution from atmospheric inputs is demonstrated by Russel (1983) whose balance between atmospheric deposition and leaching shows virtual absence of net nutrient losses from rainforest, mature pine plantation and even from an 18 months old second rotation in Brazil. In some forest sites in Latin America, potassium additions through rainwash were more than twice the amount added through litter decomposition (Fassbender 1977; De las Salas 1978).

The capture of nutrients in windblown fine soil particles around tree shrub bases represents another process of atmospheric deposition. In the same way accumulation of windblown seeds near trunks can increase herb growth and lead to greater organic matter accumulation under the canopy.

iii) **Stemflow and throughflow**

Throughflow, the process of rain dropping from canopy leaves; and stemflow, rain flowing down tree stems, represent another source of nutrient input although there is a distinction between leaching of nutrients from leaves, which is recycling, and washing atmospheric deposits from leaves, which is nutrient capture.

iv) **Animal dung**

Another input of nutrients, as yet not fully explored, is the accumulation of animal dung (mammal and bird) under trees. Large amounts of dung and urine observed under *A. albida* might explain increases in soil nitrogen and carbon recorded under the canopy (Radwanski and Wickens 1967) although the same increases were achieved when grazing animals had been excluded for 19 years (Charreau and Vidal 1965). The Fur people in Sudan ascribe fertilisation under *A. albida* to animal droppings rather than to any effect of the tree itself (Miehe, 1986).

v) **Root exploitation**

It is generally believed that tree roots can exploit deep soil layers (below 2m) beyond the reach of annual/pasture crops where fresh weathering products (potassium, phosphorus, bases and micronutrients) are available. The effect of nutrient capture at depth, and translocation into the plant system is known as nutrient pumping. This concept, although still hypothetical, is supported by the high concentration of nutrients found in forest topsoils compared to subsoils.

Tree rooting habits, however, differ with genetics and environment and different patterns and functions will develop in tree communities compared to individuals.

Kerfoot (1963) and Jenik (1977) indicate that for many woody species in the tropics, the largest number of roots and majority of fine roots are in the uppermost fertile portion of the profile. In constrast in arid systems trees can develop roots capable of reaching the water table, enabling them to continue growth through the dry season when surrounding surface rooting herbaceous plants become dormant. Figures for root biomass as a percentage of total plant biomass have already demonstrated differences in climatic zones. Kellman (1979) on excavation, found trees in neotropical savannas in Belize to be shallow rooting and could not explain soil enrichment under canopy by efficient nutrient pumping.

Soil analytical results from Neem and abandoned farm fallow suggest that Neem can extract considerable quantities of nutrients from inherently poor leached soils (Radwanski 1969).

Some examples of rooting patterns are given below:

Prosopis chilensis	- shallow and spreading (Nair 1984)
Lannea divaricata	- shallow and spreading (Garcia-Moya & Mckell 1970)
Prosopis juliflora	- very deep >3m (Philips 1963)
Prosopis	- deep (Sprent 1986) commonly >20m down to water table (Solbrig and Cantino 1975)
Acacia gregii	- Garcia-Moya and Mckell (1970)
Cassia armata	- Garcia-Moya and Mckell (1970)

Nutrient cycling

Tree based natural systems are characterised by efficient nutrient cycling and more efficient utilisation of nutrients already in the soil or those added from outside. This is achieved through the maintenance of a relatively closed nutrient cycle in the soil-forest system.

The soil-plant system is partitioned into several compartments. Most nutrients are stored in the biomass or topsoil, although the distribution of nutrients between these compartments varies between sites. A constant cycle of nutrient transfer operates from the different compartments through physical and biological processes of rainwash, root decomposition and plant uptake (Nair 1984).

The amounts of nutrients lost from such a system are negligible. Studies of phosphorus and potassium cycles in Panama reveal total gains and losses make up only 5% of phosphorus and potassium in the internal cycle, showing that this forest can maintain a nutrient cycle that is 95% closed (Golley et al 1975). In contrast annual cropping sytems are open. They experience large losses of nutrients in harvest, erosion and leaching, consequently relying on large inputs.

Research also indicated that plantation crops have the ability to cycle nutrients efficiently. Santana and Cabala-Rosand (1984) demonstrated outstanding nutrient use efficiency in a high yielding, mature 17 year old cocoa plantation with leguminous tree shade on fertile Alfisols in Bahia, Brazil. They found the balance between inputs (atmospheric and litter) and outputs (harvest and leaching) to be positive for nitrogen, phosphorus, potassium and calcium, and neutral for magnesium (Table 12).

Nutrient cycling processes are particularly relevant to agroforestry systems because tree components have a similar effect to those in natural systems. The extent to which an agroforestry is open or closed will depend on the factors which determine the amount of nutrients exported in harvest and the amount of nutrients returned to the soil in residues.

The mechanism by which tree-based systems can maintain efficient nutrient cycling is believed to be through the capture of nutrients in soil solution by tree roots that would otherwise be lost by leaching. Tree roots exploit greater depth and volume of soil, followed by translocation of these nutrients through the plant system and the return, via litter, to the soil surface where they become available to coincident or subsequent surface rooting plants.

i) **Efficient nutrient cycling** in tree-based systems is characterised by a large root absorbing zone and a large increase of nutrients stored in the plant and topsoil compartments.

a) It is accepted that the extent of root proliferation or the volume of soil occupied by tree roots (the system sorption zone) will be larger than in herbaceous plants. Trees have longer to develop an extensive rooting system.

Different nutrient absorbing zones of complementary species can lead to greater efficiency in resource sharing. Ahn (1979) suggests that this is one of the features of a natural fallow that explains its greater efficiency over monoculture artificial fallow. Reduced root competition and greater use of rooting zone should also be the aim of agroforestry mixes.

Mycorrhizae associated with roots expand the plant root system and assist in extraction of nutrients from the soil, increasing uptake ralative to leaching. They are particularly valuable in improving plant uptake of phosphorus.

Sanchez et al (1985), in their review of soil dynamics under plantation crops, explained the magnitude of increase of exchangeable calcium and sometimes exchangeable magnesium recorded in topsoils in the fallow enrichment stage at some sites, by establishment of a nutrient cycling mechanism capable of returning quantities of bases to the soil which are released from decomposing trunks, roots and stumps of cleared former forest. It was also noted that nutrient levels do not appear to decrease under tree crops implying prevention of leaching loss. Evidence suggests that when the tree canopy is established, nutrient cycling can begin. Russel (1983) measured negligible losses of phosphorus and measureable losses of K, Ca and Mg under rainforest, *G. arborea* and *P. caribea* plantation on sandy Ultisol at Jari, Brazil. He recorded lower leaching losses during mature growth stage at 1.5 years into second rotation than those under rainforest.

b) In forest systems large amounts of nutrients are stored in the vegetation and the topsoil, although the proportion of different nutrients stored in biomass and soil is known to vary. Andriesse (1987) shows how bases are concentrated in the biomass compared to nitrogen and available phosphorus, which predominate in the soil (Fig 1). A similar distribution has been recorded in tropical forests in Latin America (Sanchez 1979). In contrast, budgets for a tropical forest in Panama found 144 kg/ha phosphorus in the vegetative store (leaf, wood, fruit) compared to 22 kg/ha in the soil store (Golley et al 1975).

Bernhard-Reversat (1982) concluded that *A. albida* and *B. aegyptica* trees of Senegal increased the magnitude of fluxes between soil and vegetation as a result of organic matter and nitrogen accumulation in the soil and nutrient cycling through litter from root zone to below canopy, although the main flux occurred via herbaceous strata. Similarly, Kellman (1979) attributed preferential nutrient capture by savanna species to ability of the trees to establish enlarged plant-litter-soil nutrient cycles due to prolonged persistence at one site, enabling herbaceous biomass and litter beneath the canopy to increase.

The extent of topsoil enrichment by nutrient cycling is not only a function of the efficiency of cycling but also of the inherent fertility of the soil. Improved topsoil fertility through additions of nutrients via tree residues is only a reflection of what is in the soil to start with.

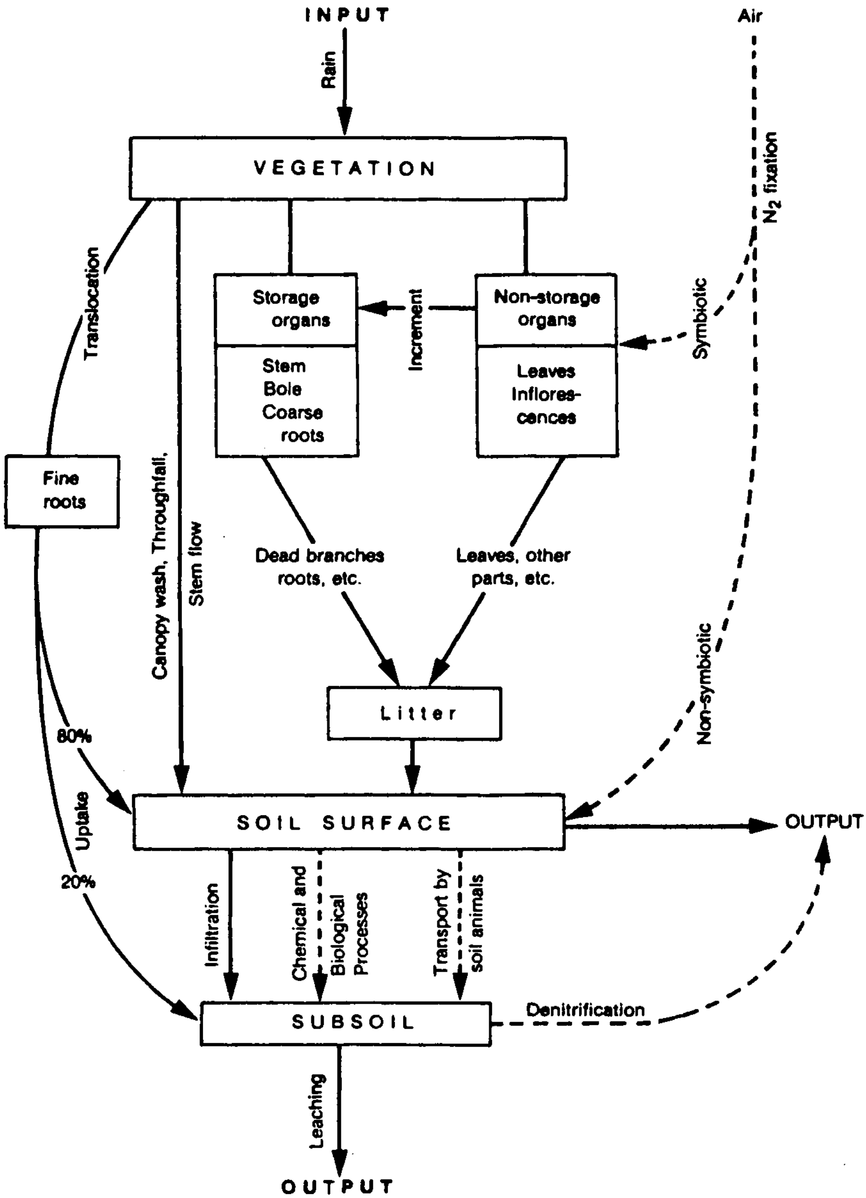
Some trees have shown potential for selectively accumulating certain nutrients. Sanchez et al (1985) report that litter and detritus from *Gmelina arborea* contained twice as much calcium as that of virgin forest or mature pine plantation while the magnesium content of litter was three times as much as in *Pinus* litter. Chijoke (1980) reports 117 and 161 kg Ca/ha/yr were returned in *G. arborea* litter for two plantation sites in Brazil. Trees that produce base rich litter have potential for checking soil acidification.

Other examples of nutrient accumulation are:

Palms and palm litter	- rich in potassium (Folkes et al 1976)
Tree ferns	- nitrogen (Mueller-Dombois et al 1984)
Cecropia spp	- Ca and phosphorus on acid soils (Odum and Pigeon 1970)
Dendrocalamus	- potassium (Toky and Ramakrishnan (bamboo India)(1982)
Heliconia spp	- available phosphorus (Tergas and Popenoe 1971)
Grass fallow	- potassium (Laudelot 1961, Lal et al (1979)
Legume fallow	- nitrogen (Pushparaja 1984) (Malaysia)

Nitrate can be taken up by some plants in excess of immediate requirements when it is freely available in soil solution and stored as free amino acids. Comparable amounts of K^{+} and Ca^{++} to NO_3 will also have to be absorbed to maintain electrical neutrality (Huck 1983).

Figure 1 Relative distribution of active amounts of main nutrients over the soil-biomass-litter compartments in Sri Lanka and Sarawak (after Nair, 1984)



ii) Nutrients stored in plants are returned to the soil through two pathways: **litter and plant cycling** (Nair 1984).

a) Litter

The amounts of nutrients returned in natural forest litter and agroforestry prunings has already been discussed in section 4. However the value of litter as a pathway for the return of nutrients can only really be appreciated from nutrient budget figures such as those prepared by Santana and Cabala-Rosand (1984) (Table 12).

b) Plant cycling

This represents the part of the total uptake of nutrients which is again leached out from vegetative parts through crown washout, canopy drip and stemflow. The amount will depend on nutrient content of leaves, frequency of rain, tree age and arrangement of leaves (Nair 1979).

Increased CEC recorded in soils under trees as a consequence of increased SOM can also improve efficiency of nutrient utilisation.

Further aspects of improved nitrogen ecnomy with trees is the possibility of reduced loss of nitrogen by denitrification and volatilisation under canopies where the environment is less favourable for these processes.

Efficient nutrient cycling is probably the key to explaining why herbaceous cropping systems cannot achieve the same benefits as tree based systems. Sanchez (1987) points out that although herbaceous plants might be able to fix camparable amounts of nitrogen and can cover the ground more quickly than tree crops, and sometimes more effectively under certain management, they cannot achieve the extent of exploration of the soil that tree roots achieve, nor contribute litter in such large amounts. The latter is a feature of time, since tree stands are still increasing, in biomass and storing nutrients long after herbaceous plants have stopped.

Nutrient budgets can be used to determine the efficiency of nutrient cycling within systems. These can simply be balances of inputs and outputs to determine net loss or gain, the size of gains and losses of nutrients compared to those in the internal cycle, or become more detailed studies of amounts of nutrients in the plant-soil storage compartments and involved in transfer in the soil-plant system. Understanding of nutrient dynamics through modelling introduces a predictive capability.

Improved moisture status

Improved moisture status under trees is achieved through canopy shade reducing evaporation and evapotranspiration and by canopy, litter or mulch dampening soil moisture flux. Resulting uniform moisture conditions favour decomposing flora and fauna.

Indirectly increased SOM will promote better structure and good pore size distribution which improve moisture holding capacity of soil. Improved surface structure and reduced runoff also favour infiltration.

TREE SELECTION AND MANAGEMENT

Given our understanding of the role of trees and processes which occur enabling soil improvement we have a good idea of what makes a tree a soil improver and therefore know what to look for in selecting trees for this purpose.

Young (1987) lists properties likely to make a woody perennial suitable for soil fertility maintenance or improvement.

1. A high rate of nitrogen fixation
2. A high above-ground biomass production
3. A dense network of fine roots, either with abundant feeder roots or a capacity for mycorrhizal association
4. The existence of some deep roots
5. A moderate to high, balanced, nutrient content in the foliage
6. An appreciable nutrient content in the root system

7. **Either** rapid litter decay, where nutrient release is desired **or** a moderate rate of litter decay, where soil cover for protection against erosion is desired
8. Absence of toxic substances in the foliage or root exudates
9. For soil reclamation or restoration, a capacity to grow on poor soils.

The potential of trees as soil improvers can only be achieved under appropriate management. Management should aim to balance gains and losses to the system by minimising loss of nutrients and biomass in harvest of tree (and crop) components and retaining those components with high proportions of nutrients, ensuring these and adequate biomass are returned to the soil. There are also opportunities to manipulate timing, state and location of residues to synchronise release of nutrients from decomposition with times of crop nutrient demand, and so improve efficiency of nutrient utilisation. The principle of maintaining a relatively closed nutrient cycle and a positive or zero nutrient balance is fundamental to cropping system sustainability. Large harvests of tree or crop components represent large exports of nutrients, and such systems which exploit tree efficiency in extracting and storing nutrients are effectively mining the soil.

Some of the adverse effects of trees listed below can result from inconsiderate management or exploitation.

Adverse effects of trees on soils

- Loss of organic matter and nutrients in tree harvest
- Nutrient competition between trees and crops
- Moisture competition between trees and crops
- Production of substances which inhibit germination or growth
- Acidification by trees which produce mor-type humus

(After Young 1987)

CROP RESPONSE

The processes described above obviously interact to achieve soil improvement although in some circumstances certain processes might dominate.

Some workers have attempted to explain improved crop growth associated with trees by single variables. Dancette and Poulain (1969) explain yield under *A. albida* by increased nitrogen content in soil and Tiedemann and Klemmedson (1973) similarly attribute greater herbage growth under *Prosopis* compared to outside the canopy to nitrogen.

It is clearly easier to look for easily measurable soil variables or short term changes to explain crop response rather than to the less tangible long term improvements of structure or reduction of insidious sheet erosion.

As defined earlier soil fertility or soil productivity is just one factor which determines crop response. Fig 2 (Huxley 1983) illustrates how many external influences at a tree-crop interface need to be considered.

Relationships between trees and understorey crops are viewed as supplementary, complementary or competitive and that which predominates depends on the growth factors that are limiting. Raintree (1983) notes a significant interaction between soil fertility and other growth factors. In some cases the effect of improved soil fertility on crops may be counteracted by competitive effects such as shade resulting in net supplementarity.

Research comparing fertilised and unfertilised soils has shown greater water use efficiency of crops when nutrients are not limiting (Hanks and Tanner 1952). Felker et al (1980), in their review, estimated that plant productivity in semi arid zones may be ten times more limited by nitrogen than by available water. Similarly research using artificial shade on cocoa plantations in Trinidad revealed that where there were adequate nitrogen, phosphorus and potassium levels in the soil, the highest yields were obtained in full sunlight but when soils were of a low nutrient status the highest yields were achieved under shade

(Murray and Nichols 1966). Similar results have been achieved from tea and coffee plantation work (Wight 1958; Willey 1975). Clearly soil fertility as a growth factor does not operate alone to determine crop response.

These examples all serve to illustrate that crop yield response does not necessarily reflect soil productivity alone.

TIME

Any assessment of soil fertility maintenance and improvement must be considered in the context of time. Perennial trees have great advantages over annual crops in terms of more time available to accumulate biomass, store nutrients and develop an effective rooting sytsem. The effect of single trees acting as nutrient reservoirs can be attributed to the processes of accumulation of nutrients and SOM over time (Kellman 1979).

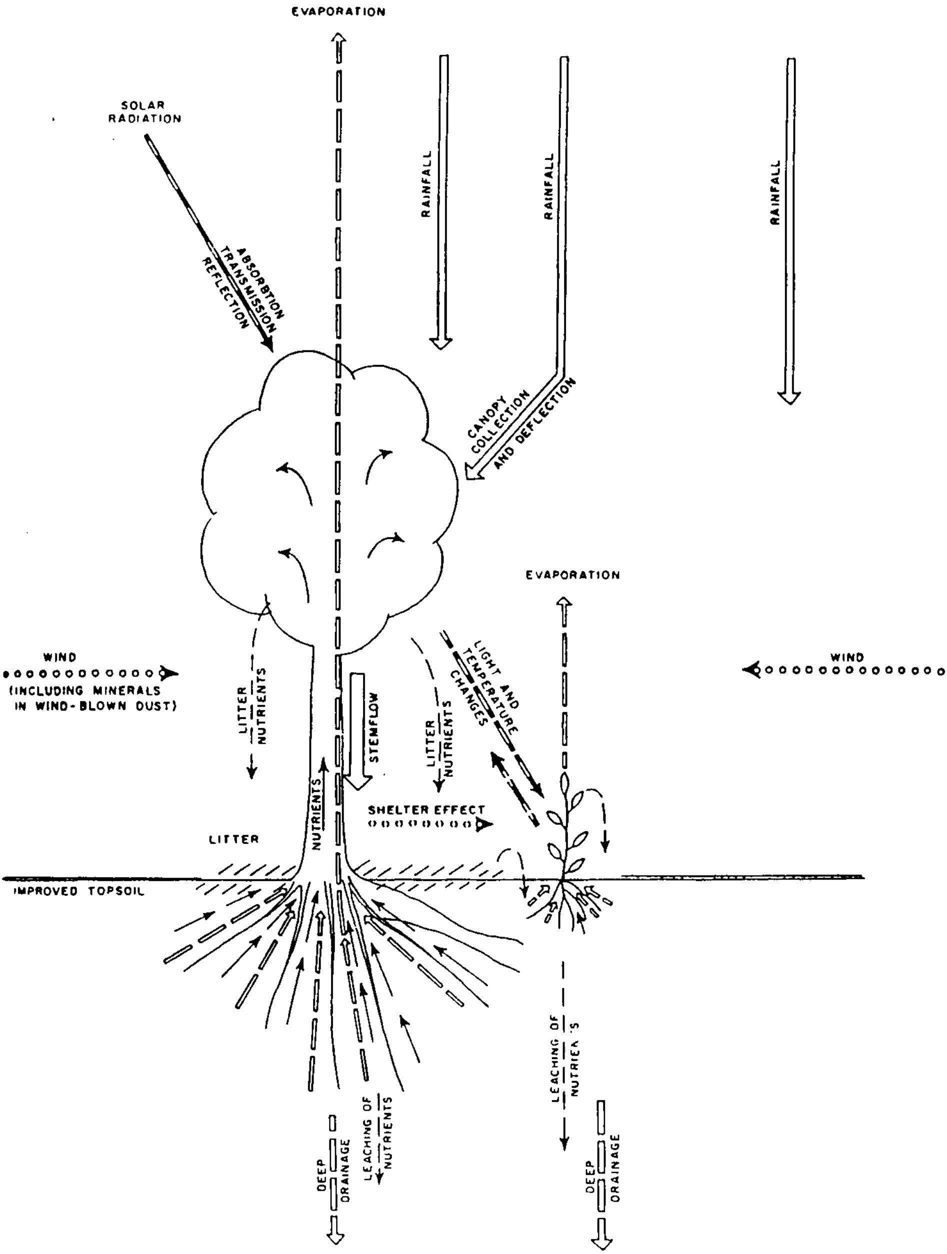
We need to consider three aspects of the time in terms of soil improvement, particularly with a view to economic analysis: how long does it take for soil improvement to become effective? How long does it continue? What are the patterns of change with time and what influences these patterns?; is equilibrium achieved? These are important both with regard to sustainability and opportunity cost considering the definitions given earlier.

Only results from those studies monitoring soil change over time at the same site can help to answer these questions. In evaluating the amount of fallow time required to restore soil fertility, the relative lengths of cultivation and fallow, expressed in terms of the R factor, are used. The R factor is defined as follows:

$$R\% = \frac{\text{years under cultivation}}{\text{years under cultivation and fallow}} \times 100$$

R values necessary to maintain soil fertility for rain forest and Savanna (burnt) have been suggested as 17–33% and 5–11% respectively.

Figure 2 External influences at the tree-crop interface (after Huxley 1983)



Okigbo and Lal (1979) state that under fallow, fertility improves with age; Ahn (1979) however argues that a fallow will have an optimum length, after which time soil improvement will stabilise.

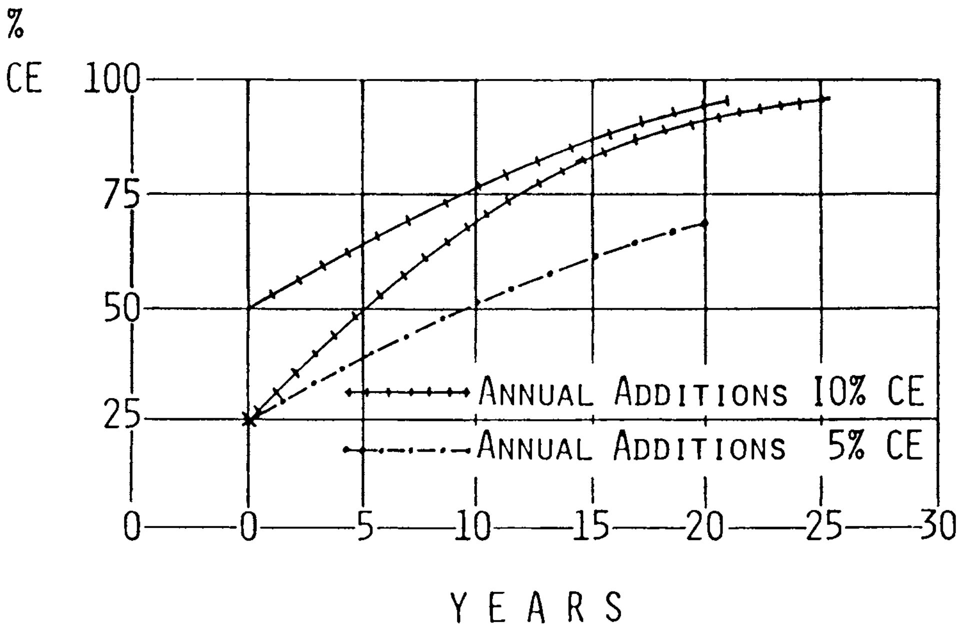
The main factors affecting the optimum length of a fallow in terms of soil improvement are environmental ones of soil, vegetation and climate which regulate rate and efficiency with which fallow brings about change. Since increases in physical, chemical and biological changes are all related to increase in humus, Ahn (1979) proposes that humus is a useful parameter which reflects changes that together increase productivity.

He suggests that optimum fallow length is the point when increase in SOM reaches equilibrium (ie when gains = losses). On the basis that the rate of humus increase depends on how far present levels are below the humus equilibrium level, additions of raw organic matter will have different effects on SOM content, depending on its initial content in relation to equilibrium. This is why Ahn (1979) explains the initial rate of SOM increase is high in fallow (when SOM is below equilibrium) and then becomes progressively lower as equilibrium is approached (see Fig 3)

The optimum fallow time, therefore, is the point when increase in SOM flattens out, reflecting the progressive reduction in size of the annual increment of humus addition. As the increment gets smaller, justification for keeping land out of production is less. Six-eight year fallow is suggested as a practical minimum for many areas although longer is required in savanna areas. It is interesting to consider opportunity costs of leaving land in fallow, particularly for the periods beyond optimum length.

Estimates have been made of the capacity of certain indigenous agroforestry systems to maintain soil productivity over time. Guilloteau (1954) suggested that 1 year's fertilisation by grazing animals of a stand of 15 *A. albida* trees/ha every 80 years was sufficient to maintain fertility for the land to be continuously cultivated without recourse to fallow. Ferguson (1949) reported that sorghum is grown continuously under *A. albida* year after year in the same areas of the Sudan and in some cases up to 30 years continuously.

Figure 3 Graphs showing calculated humus contents during fallow periods for soils with initial humus contents at 25% and at 50% of equilibrium level, receiving annual additions of humus carbon equivalent to 5% and 10% of humus carbon at equilibrium level (Ahn 1979)



The question of immediate versus long term benefits should be introduced here. Agroforestry systems, although they offer long term productivity and ecological stability, cannot compete with the immediate results of artificial fertilisers. It is quite difficult to evaluate long term, less tangible benefits commonly associated with low input systems.

LEVELS OF IMPACT

So far we have considered soil fertility improvement within a single field or forest plots. It is important to view the different levels of impact these benefits have:

Level	Effect	Immediate Beneficiary
Field	Improved yields	Farmer
Farming system	Improved sustainability	Farmer
Catchment	Hydrological benefits	Community
Ecosystem	Ecological stability	Community

Nair (1984) argues that inclusion of trees in farmland can have considerable impact by changing a farming system from one of decline to one of sustainability because improved productivity and introduction of multi-purpose trees brings stability to the system.

Felker (1978), in considering the combined effect of all increases which result in increased fertility and crop yields on smallholdings in the Sahelian zone, postulated that the presence of *A. albida* on a farm could increase carrying capacity from 10–

20 to 40–50 persons/km^2. It would be interesting to consider the effects on farm sustainability of removal of *P. cineraria* in W Rajasthan where they occur at densitites of 150/ha in pearl milet fields.

Secondary benefits of improved soil productivity under trees can be accrued to the community as a whole. There is evidence that hydrological characteristics of catchment areas are favourably influenced by the presence of trees while the benefits of trees in soil conservation and erosion are extended to the whole ecosystem.

CONCLUSION

Improved soil fertility, soil productivity or soil conservation and reduced soil degradation are often attributed to the beneficial effects of trees on soils. The importance of defining these improvements and standardising methods and units of their measurement, particularly with regard to preparing for economic evaluation, has been discussed.

The improvement of soils by trees is service rather than product orientated, making conventional economic assessment difficult. Furthermore these benefits are not yet fully proven for agroforestry systems and are known to vary under different conditions of environment and management.

Despite the obvious potential of trees as soil improvers, the evidence is mostly indirect and some of this should be viewed with caution, particularly in interpretation and extrapolation to agroforestry systems in differing environments. Similarly our understanding of the processes involved, although advanced, is still hypothetical and further work is needed to validate the hypotheses. Modelling of these processes will introduce a predictive capacity and the opportunity to investigate the economic consequence of introducing certain agroforestry interventions.

The benefits associated with tree cover and methods of measurement are summarised in Table 13. We must explore whether it would be desirable to assign economic value to improvements in

Table 13 Summary of benefits associated with tree cover and standard methods of measurement.

Benefits	Measurement
Increased or maintained SOM	Total organic carbon Functional pools - light fraction, heavy fraction, microbial carbon Biomass produced by tree components Loss of topsoil C by oxidation or erosion
Improved structure	Bulk density Infiltration capacity Aggregate stability and size Pore size and distribution SOM AWC
Increased nutrient status	Total nitrogen Available phosphorus Exchangeable bases Micronutrients
Erosion control	Erosion tonnes/ha/yr Nutrient loss kg/ha/yr SOM loss kg/ha/yr Surface structure Infiltration capacity
Improved moisture status	% moisture AWC
Efficient nutrient cycling	Net gains or losses Nutrient returns in biomass kg/ha/yr Nutrient losses in harvest Nutrient losses in leaching/erosion Net gains and losses in relation to internal nutrient cycle
Improved productivity	Soil changes over time Yield
Improved sustainability	Yield stability or degree of variation over time.

soil characteristics and qualities or to the effect of these improvements ie improved sustainability or yield increase.

Assessing the degree of SOM conservation and efficiency of nutrient cycling are two methods that allow some evaluation of internal regulation and sustainability. Interaction of growth factors at the tree-crop interface, however, complicate the use of crop yield as a reflection of soil productivity.

It is important to remember that the farmers' aim is food production and that a productive and perhaps equally sustainable system might be achieved by use of manures/inorganic fertilisers and appropriate tillage in other cropping systems. Clearly some method of comparing relative benefits for farmers is needed.

Finally we can look to the farmer as being the most experienced economist for his farming system. However, whilst he might have adopted the most economically viable system for given resource constraints, this may be targeted towards immediate productivity at the expense of long term economic and ecological stability.

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FOLIAR NITROGEN LEVELS OF SOME DRY ZONE HARDWOOD SPECIES IN MALAWI.

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CONTENTS

Abstract

Foliar nitrogen levels were determined as an index for screening tree species for a project investigating the effects of trees on soils.

Mid crown leaves of *Leucaena leucocephala, L. diversifolia, Albizzia caribaea, A. guachepele, Gliricidia sepium, Enteralobium cyclocarpum, Crescenta alata, Senna atomaria, Guazuma ulmifolia, Acacia farnesiana* and *A. deamii* were analysed for foliar nitrogen by the wet digestion method.

The results indicate *Leucaena diversifolia, Crescenta alata, Enterolobium cyclocarpum* and *Gliricidia sepium* as the top four with values above 2%. However these values need to be linked to foliage biomass production. Field observations indicate that *G. sepium* produces more foliage than any of the other ten species. It is therefore considered the most appropriate for use in the soil amelioration project which aims at understanding processes of tree-crop-soil interactions where woodlots are used to contain land shortage and address lowered soil fertility and wood resource scarcity.

Introduction

Malawi has a population of almost 8 million people spread over a land area of 94,270 square kilometres. This works out to almost 85 persons per square kilometre, which is among the highest in Africa.

The country heavily depends on rainfed agriculture whose smallholder subsector accounts for just over 80% of total production. This subsector meets the national requirement for basic foodstuffs and a little surplus for export (Malawi Government, 1984).

Steady growth of the subsector due to high population growth has meant converting forestland to agricultural land. Consequently, wood resource is a scarce commodity and it is largely the marginal land that is available for afforestation. This marginality means poor rainfall, stoney or massive lateritic soil, waterlogged sites and lowered soil fertility due to overcultivation.

Suitable species are, therefore, required for planting on these difficult sites. Screening species on the basis of their adaptability to the sites as indicated by survival rates, diameters at breast height and tree heights have been the concern of a Fuelwood and Polewoood Research project for the Rural Population of Malawi. This Project was funded by the International Development Research Centre (IDRC). In addition to the above parameters, foliar nitrogen levels were determined as an index for the tree species' ability to ameliorate soils through litter fall.

Materials and Methods

Mid crown leaves of *Leucaena leucocephala, L diversifolia, Albizzia caribaea, A. guachepele, Gliricidia sepium, Enterolobium cyclocarpum, Crescenta alata, Senna atamaria, Guazuma ulnifolia, Acacia farnesiana* and *A deamii* were sampled in February 1989 from 2 year old trees growing on a fairly acidic sandy loam soil which is deficient in total nitrogen as indicated in Table 1.

The leaves were oven dried at 80°C overnight, ground and subsamples digested with concentrated sulphuric acid. The digests were distilled into Boric acid which was back titrated with N/70 solution of hydrocholoric acid.

Table 1 Soil properties of topsoil (0–20 cm layer) at Naminyanga dry zone hardwood elimination trial as at planting.

Sand, %	67
Silt,%	12
Clay,%	21
Bulk density, g cm^{-3}	1.37
Waterholding capacity, cm cm^{-3}	1.37
pH	5.5
Organic matter, %	12
Total nitrogen, %	0.10

Results and Discussion.

Leucaena diversifolia, Crescenta alata, Enterolobium and Gliricidia sepium are the top 4 tree species in foliar nitrogen as indicated in Table 2.

Table 2 Foliar nitrogen leaves of dry zone hardwood species growing at Naminyanga

Species	N% (oven dry mass) ± Std
Leucaena diversifolia	2.19 ± 0.80
Crescenta alata	2.66 ± 1.42
Enterolobium cyclocarpum	2.64 ± 1.70
Gliricidia sepium	1.97 ± 0.98
Albizzia caribaea	1.93 ± 1.38
Albizzia guachepele	1.76 ± 0.32
Acacia farnesiana	1.76 ± 0.32
Senna atomaria	1.72 ± 0.34
Guazuma ulmifolia	1.49 ± 0.16
Leucaena leucocephala	1.36 ± 0.48
Acacia deamii	1.01 ± 0.47

The foliar nitrogen levels serve as a crude index for screening species ability to ameliorate soils and provide good fodder. However the index needs to be linked to foliage production. The importance of this linkage can be demonstrated by *Gliricidia sepium* which is ranking fourth in Table 2. Field observation indicate that *G. sepium* produces more foliage than any of the other species in the table. It is therefore expected to rank first on total foliage nitrogen when the foliage biomass data is taken into account.

The data in Table 2 together with information on growth (Ngulube, 1986) provide background information to a Commonwealth Science Council project on 'Amelioration of Soils by Trees'. This project aims at understanding the processes involved in the tree-crop-soil interactions where woodlot agroforestry practice is used to contain land shortage and address lowered soil fertility and wood resource scarcity (CSC 1987). The collaborating partners are the Forestry Research Institute of Malawi (FRIM), a smallholder farmer in Malawi, Department of Soil Science at the University of Reading (UK) and the Department of Biological Sciences at the University of Exeter (UK). Cost benefit analysis will be done to compare this situation against one without the woodlot.

Conclusions

Foliar nitrogen levels need to be linked to foliage biomass production in order to improve their role as an index for screening tree species for use in amelioration of soils by trees programmes. Although *Leucaena diversifolia* ranks high on foliar nitrogen per cent, *Gliricidia sepium* (fourth on the per cent scale) produces more foliage than any of the other ten tree species investigated in this study.

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ECONOMIC CONSIDERATIONS OF ALLEY CROPPING FOR FOOD PRODUCTION IN SEMI-ARID AREAS

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Introduction

Kenya's arid and semi-arid areas cover approximately 83% of the country. The semi-arid areas with marginal to medium agricultural potential comprise about 21% of the total land area (Braun and Mungai, 1981).

In the past two decades, because of population pressure, there has been considerable human migration from the high potential areas to the medium and more recently to the low potential ones. this trend is likely to continue at an increased rate and calls for an effort to both increase and stabilize food production in these areas. According to Government policy, one third of the projected increase in agricultural production in Kenya is expected to come from new acreage largely in the semi-arid areas (Government of Kenya, 1983). Thus, it would seem these areas will play an important role in human settlement as well as in the production of subsistence food as people in the more favoured areas opt for food and also cash crops.

The major environmental factors limiting crop and animal production in the semi-arid areas of Kenya are rainfall and soil fertility. The average annual rainfall is low and in much of the country it is divided into two rainy seasons of short duration. The seasonal rainfall is not only unrealiable but also has poor distribution. The climatic problem is especially enhanced by the high evaporation rates occurring in the semi-arid areas. The intense and most erosive rainstorms occur in the first few days of the rainy season when the vegetative cover is low which gives rise to high erosion rates (Moore 1978). The high intensity storms not only reduce the quantity of water available to crops, but also lead to reduced plant nutrients in the top soil through leaching. The net result of this is land degradation and reduced productivity from the land. However, the soil fertility problems in the semi-arid areas are not only related to the loss of top soil but also to the relatively low turnover of organic matter in the soil.

Apart from these environmental problems, the farming enterprises in the semi-arid areas have been dominated by repetitive maize/bean (or other legumes) intercrops and low agricultural inputs. This crop management system is risky in the face of unfavourable conditions such as weather vagaries and disease and pest attacks. Failure of crops has often necessitated expensive Government intervention in the form of famine relief. With the increasing population and low and unsustainable yields in the semi-arid areas, it would appear that a practice of mixed **sustainable** cropping is a more viable alternative even though yields may be lower than those in the high potential areas.

A major response to these problems has been the introduction of agroforestry (various interventions) as a low input technology to sustain crop production as well as offer other benefits to the farmer. The Kenya Forestry Research Institute (KEFRI), in conjunction with the Machakos Integrated Development Programme (MIDP) and other relevant Government and Non-Governmental organisations, are involved in a major research effort in alley cropping in the semi-arid areas of Machakos district. Alley cropping is essentially an agroforestry system in which food crops are grown in alleys formed by hedgerows of trees or shrubs (Kang et al 1981; Wilson and Kang, 1981; Kang et al 1984). KEFRI is interested in the potential of alley cropping for soil nutrient increase and other improvements of growing conditions for small-scale farmers in the semi-arid areas, as well as other benefits eg fodder and fuelwood (Arap Sang and Hoekstra, 1986).

The aim of this paper is to give a preliminary technical evaluation of the biological potential of alley cropping in semi-arid areas based on ecophysiological research carried out at the National Dryland Farming Research Station, Machakos, during 1987 and 1988 as well as to suggest relevant variables for a cost-benefit analysis of the system. Since a strict definition of economics is not easy (Todaro, 1977), the economic evaluation of a farming system, such as alley cropping, should take into account changes of the principle economic components which may result from changes in the system's management. This is because a change in the management aspects of the system could radically alter the principle components used in its evaluation. For example, the production of useful wood from an alley cropping system might be a different economic component compared to the possible impact the mulch input might have on crop production in the crop and this change in the principle economic component has been brought about by a change in the management of the system. A great temptation when discussing agroforestry interventions from an abstract economic view is to extend, unreasonably, the concept of multipurpose trees. Great care must be excercised in applying the "multi-purpose" tree concept to all climatic conditions, especially in semi-arid areas. The underlying problem is that the potential uses of a tree may vary depending on the rainfall and the management of the proposed intervention. Without serious consideration of the biological aspects it is very tempting to fall into the "designer tree" syndrome (Coulson 1989). You can't get everything for nothing!

The reported ecophysiological data were gathered under the umbrella of the TTMI-Project, the University of Nairobi and the National Council for Science and Technology. The TTMI- Project also operates in the Sudan and Tanzania investigating diverse agricultural research problems of critical relevance to small scale subsistence-oriented farmers. The project is based at the Agricultural University, Wageningen and is funded by DGIS (The Netherlands).

Overview and the experiments

The experimental site belongs to the National Dryland Farming Research Station which is about 7km from Machakos town (approximately 1½ 30'S, 37½ 15'E; altitude 1560m). The average annual rainfall and potential evaporation are about 700mm and 1800mm respectively. The average seasonal rainfall for each of the so-called "long-rains" and "short rains" is about 300mm. The soils of the experimental site are Luvisols; they are well drained and deep (80-120cm) with friable clay over murram. The top soils have low (< 1%) organic matter content.

The established experimental layout is a randomised design with two treatments (excluding the control) replicated four times. *Cassia siamea*, which is non-leguminous, had been previously selected as the tree species for the hedgerows. Within each plot, except in the controls, four hedges have been established since November 1983, at between - row spacing of 3.6m. In row spacing of *Cassia siamea* is 0.25m for treatment 1 and 1m for treatment 2. In between two hedgerows, three rows of Katumani

Composite B maize are planted parallel to the hedgerows at a spacing of 90cm by 30cm. In the control plots, each hedgerow is replaced by a row of maize. The established practice is to incorporate the loppings of *Cassia siamea* into the soil at the beginning of the season. The experiments described here were done in the 0.25m spacing and the controls.

From the early work of the Dryland Agroforestry Research Project (1903-1985), it appeared that during the development period of the alley cropping system, the maize rows adjacent to the hedgerows outperformed the centre rows perhaps due to improved availability of moisture, light and nutrients. When the hedge was better developed, a negative impact was noted on the maize rows closest to the hedges most likely due to competition for soil moisture and nutrients between the hedges and the maize (arap Sang and Hoekstra, 1986).

In an integrated quantification approach, the "Traditional Techniques of Microclimate Improvement" Project began in late 1986 involving collaborative research with the various institutions. The TTMI - Project has three main aims (Mungai et al, in prep) i.e:

a) to train local scientists though working on local problems

b) to demonstrate the need to study the interactive relationships between micrometeorological (aerial and soil) and plant parameters in agroforestry systems, as they relate to yield sustainability and the conservation of the environment.

c) to develop appropriate methodologies and equipment for environmental quantification of AF on-station and on-farm conditions.

In this paper, we will deal with objectives (a) and (b). Some aspects of (c) are discussed by Coulson and Taylor (1984), Couslson and Stigter (1988), Coulson et al (1988) and Coulson and Musyoki (in press).

Preliminary results and implications for cost-benefit analysis

Of all the parameters being quantified, soil moisture as determined by amount and distribution of rainfall and nutrient availability, appears to be the most important in determining the growth and yield of Katumani Composite B maize in Machakos.

"Long rains", 1987

The seasonal rainfall (March-May) was below the long term average. Gravimetric soil moisture measurements indicated higher percentage moisture in the top soil of treatment plots compared to the controls - a treatment effect due to mulch incorporation in the *Cassia* plots. However, the sub-soil in the controls was wetter that in the *Cassia* plots. Transpiration and photsynthetic rates were higher in the controls than in the *Cassia* plots. The control plots lost slightly more maize plants than the treatment plots but the differences were not statistically significant. No statistically significant differences were found for the grain yields.

"Short rains", 1987

The rains were late, low in amount and poorly distributed. Because of this, there were marked contrasts in the performance of the maize. The percentage number of dead plants was higher in the *Cassia* plots than in the controls. This difference, which was reflected in the grain yield data, was statistically significant at the 95% level. The differences in the survival rates of the maize plants were largely due to competition for water. Soil moisture measurements, using gypsum blocks, indicated wetter conditions in the controls. A recent preliminary study of the root distribution of *Cassia siamea* indicated that at a distance of 75cm from the trees, 56% of the roots occurred in the top 40cm of the soil. At 40cm from the tree 63% of the roots were found in the top 40cm of the soil. This surprisingly shallow rooting depth of the *Cassia siamea* seems to explain the competition for both water and possibly nutrients that were observed during this season.

"Long rains", 1988

The rainfall this season was above the long term average and also well distributed. This maize grew fast early in the season and quickly surpassed the height of the *Cassia siamea* hedgerow. Thus compared to the previous seasons, soil moisture was not a major limiting factor. Based on the total planted area, the mean grain yield of the *Cassia* plots was 2.6 t/ha compared to 2.8 t/ha for the controls. The difference in the mean grain yield was not statistically singificant at the 95% level.

Discussion

From these results, it appears that competition for growth resources eg space, water, light and nutrients etc between the annual crop and trees or hedges in an alley cropping system obviously has implications for the productivity of the crop. When the perennial part of the system over-competes with the crops, the crop yields will be reduced. If we consider competition for water within the sytem then this will obviously be a function of rainfall. If water resources are plentiful, then competition between the crop and the hedge will be minimal or non-existent. With a reduction in the available water, competition will start to occur between the two parts of the system. The degree of competition will depend on the density of component plants and, importantly, on the soil horizons from which they predominantly extract their water. The experiments described here strongly suggest that the productivity of the maize crop in the alleys relative to that not in the alleys is very much influenced by rainfall. In seasons of good rainfall, the productivity of the maize in the alleys (fewer maize rows) is not statistically different from that in the controls. This is probably the result of increased soil fertility due to mulching. During poor rainfall seasons, however, the productivity is reversed in that the maize in the controls is more productive than the maize between the *Cassia*. This would seem to suggest that in the alleys, the *Cassia* 'won' and the maize 'lost' when water was limited. This raises the idea that as rainfall declines, the alleys becomes less productive and at some rainfall figure, the maize in the *Cassia* plots has the same productivity as the maize in the controls. Further rainfall reduction makes the productivity of maize in the controls greater than that in the alleys where, under such limited rainfall, the competition by *Cassia* for water is too great. A 'break-even' rainfall could be typical on all alley cropping systems though the actual rainfall value would be expected to vary depending on various factors eg soil moisture retention and release characteristics, duration and distribution of the seasonal rainfall, and rooting patterns of the component plants (Coulson, unpublished).

One of the important factors that will influence the degree of competition between the hedges and maize will be the depth of rooting of these two components. If the rooting depths are similar, then we would expect appreciable competition. The observations on maize yield and *Cassia* rooting seem to confirm this.

The relationship between the shoot and root mass in plants has been studied for many years. Such studies indicate that within a species, there is a relationship between the mass of the shoot and that of the root. Although to some extent, this relationship is plastic it is probably true to say that the greater the extent of the shoot, the greater is that of the root. It is conceivable that reduction of the shoot system of some trees reduces the root system in such a way that water extraction takes place from the upper parts of the soil profile. This situation would encourage or increase competition between the *Cassia* and the maize for both water and nutrients. The continous lopping of the *Cassia* down to 50cm in the experiments described above could be the reason for the apparent shallowness of the rooting system of the *Cassia* and the competition patterns at low rainfall. To avoid or at least to reduce such competition, the tree component of the alleys should preferably extract water from a lower soil depth than the maize. To engender the situation, it may be profitable to consider a reduced lopping regime to increase the shoot mass thereby increasing the root mass, allowing water extraction from deeper soil layers. This principle would be more applicable to hedge trees/shrubs which tend to develop tap root systems. However, it must be realised that an increased shoot mass could lead to increased lateral root growth and perhaps greater competition of the tree with the maize. One concept is that in semi-arid regions, alley cropping which involves heavy pruning may be counter productive (taking all production functions into account) and a reduced pruning regime coupled with a reduced density of the tree component may be a better solution. This concept could be approximated by the following:

Pruning Height Regime = f(1/rainfall and tree density)

If this concept (Coulson, unpublished) leads to a viable management practice, the question then arises as to the effect on the economics of the system. Presently under the heavy pruning regime of the *Cassia* hedges, the pruned material is used as mulch to increase soil fertility and to improve other growth conditions. An economic benefit would be expected to be a reduction in the chemical fertilizer input. If the rainfall is such that it is better to have larger and fewer trees, this economic benefit of the system may change. Under these circumstances, the production and monetary value of poles or wood would probably be higher. Some mulch from natural litter fall may still be expected to occur and indeed the deeper roots of the trees could bring nutrients to the rhizosphere which might otherwise, because of shallower roots, be lost to the system.

Other relevant economic considerations

a) Opportunity costs for land and labour. These should be assessed according to the constraints and production objectives of given farmer categories.

b) The economics of relevant training. With good training based on local problems, it would be expected that well directed research would be carried out in the many 'grey areas' of agroforestry to understand cause-effect relationships or to develop relevant methodologies. Perhaps the aspirations of national research priorities do not show sufficient emphasis on the fact that the skills required for agroforestry research are not normally available in the scientific pool, particularly in the developing countries. Thus, the cost of providing a good manpower base for AF research is underestiamted and the long term implications not fully appreciated.

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THE TECHNICAL COSTS AND BENEFITS OF AGROFORESTRY TO THE CATCHMENT AS A WHOLE. UPSTREAM–DOWNSTREAM RELATIONSHIPS

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Introduction

All interventions in the management of areas within a catchment will have implications for the environment elsewhere in that catchment. Specifically, land management programmes in the upstream zone may have profound impacts on the areas downstream. These impacts may be beneficial or deleterious, but either way should be included in any environmental impact assessment or economic review of the upstream programmes. All too often they are ignored. This may well be largely due to technical constraints; it is very difficult to predict upstream-downstream reactions in terms of altered runoff or sedimentation amounts or distributions. This is because the processes involved are extremely complex. Most of the computer models which exist for predicting catchment scale discharges or sediment yields rely on calibration of parameters for an **existing** situation. To reliably predict the impact of a proposed catchment management change is almost impossible.

Because these types of question have only just begun to be considered by the technical world, especially with respect to the tropics, there is a dearth of data on which to base any hypotheses. This lack of data, and the complexity of the physical processes involved, mean that we are often unable to give economists estimates of the wider scale effects of intervention on which they can base a cost-benefit analysis.

There is also the question of the time scale of effects. Does it matter if sediment yields to a downstream reservoir decrease, if there is already enough sediment in the river valley to fill the reservoir anyway? In this case the benefits of upstream catchment protection will have no effect on the reservoir in the short-term. If the sediment stored in the valley is only a fraction of that needed to fill the reservoir, it is still likely that the reservoir will continue to fill at a rapid rate until the valley sediments are exhausted. Only then will the reservoir benefit from the upstream management changes. These benefits in the future are, in economic terms, of less worth than any immediate benefit. But, what if there are no alternative sites for reservoirs, and the water from the reservoir is important for power generation or irrigation? Then maybe there is an argument that protection of the reservoir should be worth more than the simple discounted value of benefits in the future. This, however, is a question of economics rather than a technical one!

In this paper I am aiming to review what is known of the technical costs and benefits of agroforestry to the catchment as a whole. I will augment this with experience we have gained in Africa and Asia on the movement of sediment through the catchment, and the effects of different land management techniques in reducing runoff and soil loss.

What are the impacts of agroforestry, in terms of supply of sediment and water to areas downstream?

A review of the role of agroforestry as a means of soil conservation (ie reduced soil erosion) carried out by Young (1986) shows that there is little data specific to agroforestry. An exception is the work by Wiersum (1984), who reviews various measured rates of soil erosion by water under agroforestry systems. Much other work assesses the likely impact of agroforestry, by considering it as a hybrid, somewhere between forest and cropped land. In this paper I am not going to attempt to put values to the soil erosion or water yield from different agroforestry systems. I am instead going to look at the trends that may exist, and try to show how the effect of these trends can be evaluated for the catchment as a whole. In other words, I am going to present important concepts and relationships, which must be understood if impact on the catchment is to be successfully assessed.

There is a general feeling that agroforestry is good in terms of reducing soil erosion. This may not always be so, being dependent on the type of agroforestry that is implemented. Pereira, quoted in Hamilton and King (1983), cites a demonstration of agroforestry in which maize and pineapple were planted between rows of pine trees, straight up and down 20% slopes - this cannot be expected to reduce soil erosion! On the other hand if properly implemented, with due consideration to sensible soil conservation practices, there is evidence that soil losses may be comparable with those under forest. Recently the idea of converting forest to agroforestry use has gained in popularity. If properly managed the impact on runoff and soil loss may be dramatic, but it must always be remembered that the potential for disaster is there, when a stable eco-system is disturbed. The effect of the conversion also depends on the way in which it is carried out. So, we must look at downstream impacts in terms of either an increase or a decrease in eroded soil from the agroforestry site.

The effect of agroforestry on runoff is just as unpredictable. Hamilton and King (1983) discuss a case in Kenya, where forest was changed to tea plantation plus shade trees. Here, although the total annual yield of water was not changed, both low flows and peak flows were increased. This redistribution of flows, and especially any increase in peak discharge, has profound implications in terms of the sediment carrying capacity of rivers. This point will be pursued later.

It is likely that if agroforestry replaces a previous unstable agricultural use, both total annual runoff and peak discharge will be reduced. With this scenario low flows are also likely to be reduced, due to the higher consumptive water use of trees, and indeed of intensive agriculture. Again this redistribution of flow frequencies has implications for river sediment transport.

Confirmation of these relative values of discharge, and the potential reductions in soil loss comes from a comparative catchment study in Malawi (Amphlett, 1986). The results are summarised in Table 1 and Figures 1, 2 and 3. Although none of the catchments are under agroforestry, the completely managed catchment at Bvumbwe which combined both physical and biological conservation techniques, shows the benefits which can be obtained. This catchment encompasses the one thing that is often quoted as the most important factor for agroforestry systems in reducing erosion, namely a high percentage of soil cover. This good soil cover was also present in the plantation catchment at Mphezo. Perhaps the results for agroforestry would lie somewhere between these two catchments. Physical conservation alone is not nearly so effective (Mindawo II catchment), although it gives vast improvements when compared with the traditionally farmed, Mindawo I catchment.

Table 1

Summary of results from the catchment study in Malawi

	SEASON	BVUMBWE (full land use plan)	MINDAWO (traditional cultivation)	MINDAWO II (physical conservation)	MPHEZO (plantation)
Rainfall	1981/82	957	890	-	-
(mm)	1982/93	822	910	975	951
	1983/84	836	865	914	923
	1984/85	1334	1191	1207	1137
Runoff	1981/82	29.7	81.0	-	-
(mm)	1982/93	19.0	156.7	54.8	7.7
	1983/84	6.7	42.0	17.4	4.2
	1984/85	62.2	154.5	85.6	8.4
Soil loss	1981/82	0.12	10.06	-	-
(t/ha)	1982/93	0.21	13.70	2.31	0.092
	1983/84	0.03	4.44	1.18	0.028
	1984/85	0.13	14.32	5.11	0.058

Further similar work in the Philippines, on two small reforested catchments at Dallao, gave similar low values of runoff and soil loss (Table 2). Again good soil cover is the primary reason for the decrease in erosion.

The magnitude of effect which agroforestry has on the catchment as a whole, depends on the percentage of the catchment which is under agroforestry. If 2% of the catchment area, somewhere up in the mountains has agroforestry applied it is probable that little effect will be noticed at the outlet of the larger catchment. But, if the percentage under agroforestry is 98%, changes at the catchment outlet may well be very distinct. Pitman (1978) in a study of trends in streamflow due to upstream land use change shows mean annual runoff decreasing almost linearly with increasing forest area (Fig. 4). A similar picture may be expected for agroforestry, which also shows fairly high evapotranspiration rates.

Table 2

Summary of results from reforested catchments at Dallao, Philippines

	Year	Rainfall (mm)	Runoff (mm)	Soil loss (t/ha)
Catchment B	1984(J-D)	937.85	70.53	0.082
	1985	2035.02	336.18	0.995
	1986	1791.92	245.47	0.199
	1987	1179.55	129.36	0.171
Catchment C	1984(J-D)	864.42	71.36	0.111
	1985	1833.64	341.41	0.770
	1986	1615.86	203.77	0.390
	1987	1076.12	-	-

Figure 1 Cumulative runoff records for 1981/82 & 1982/83 seasons

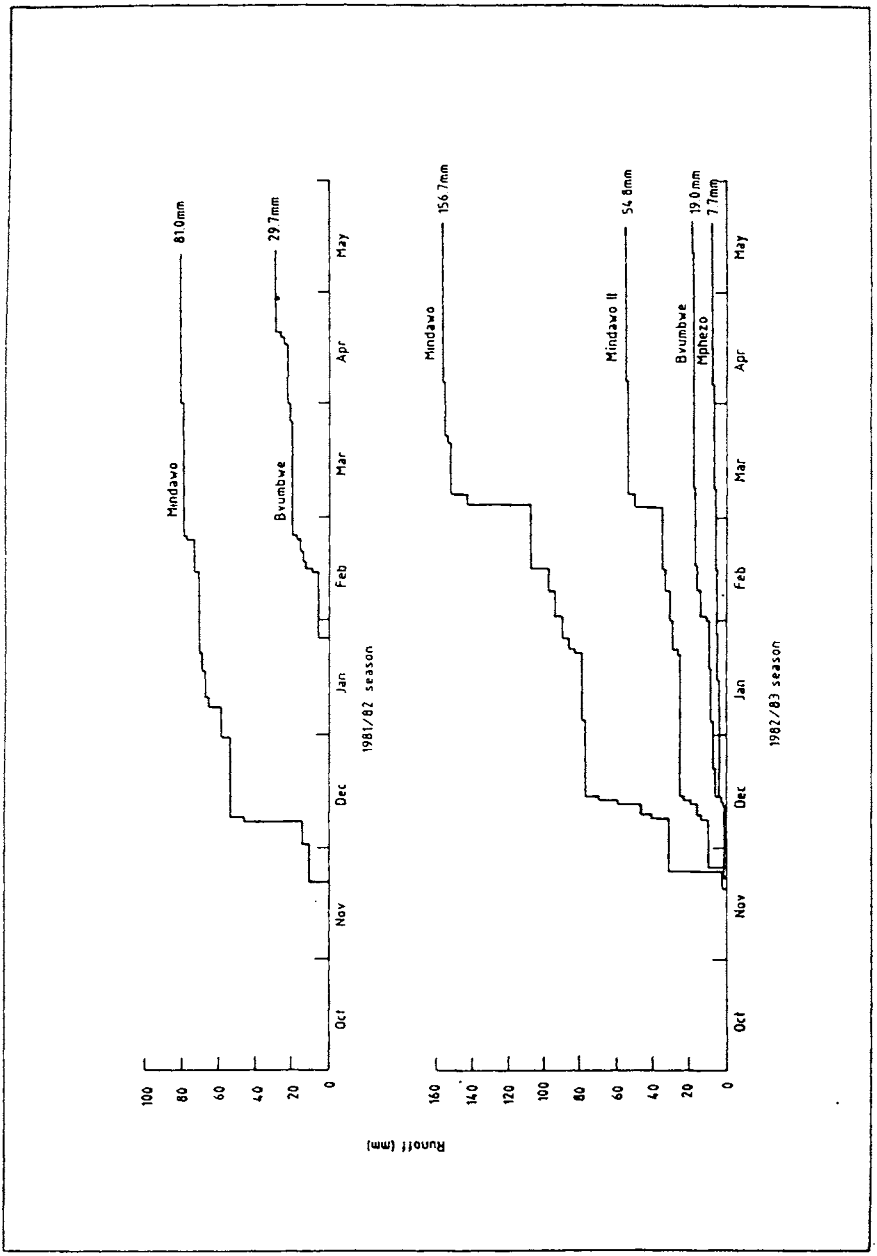
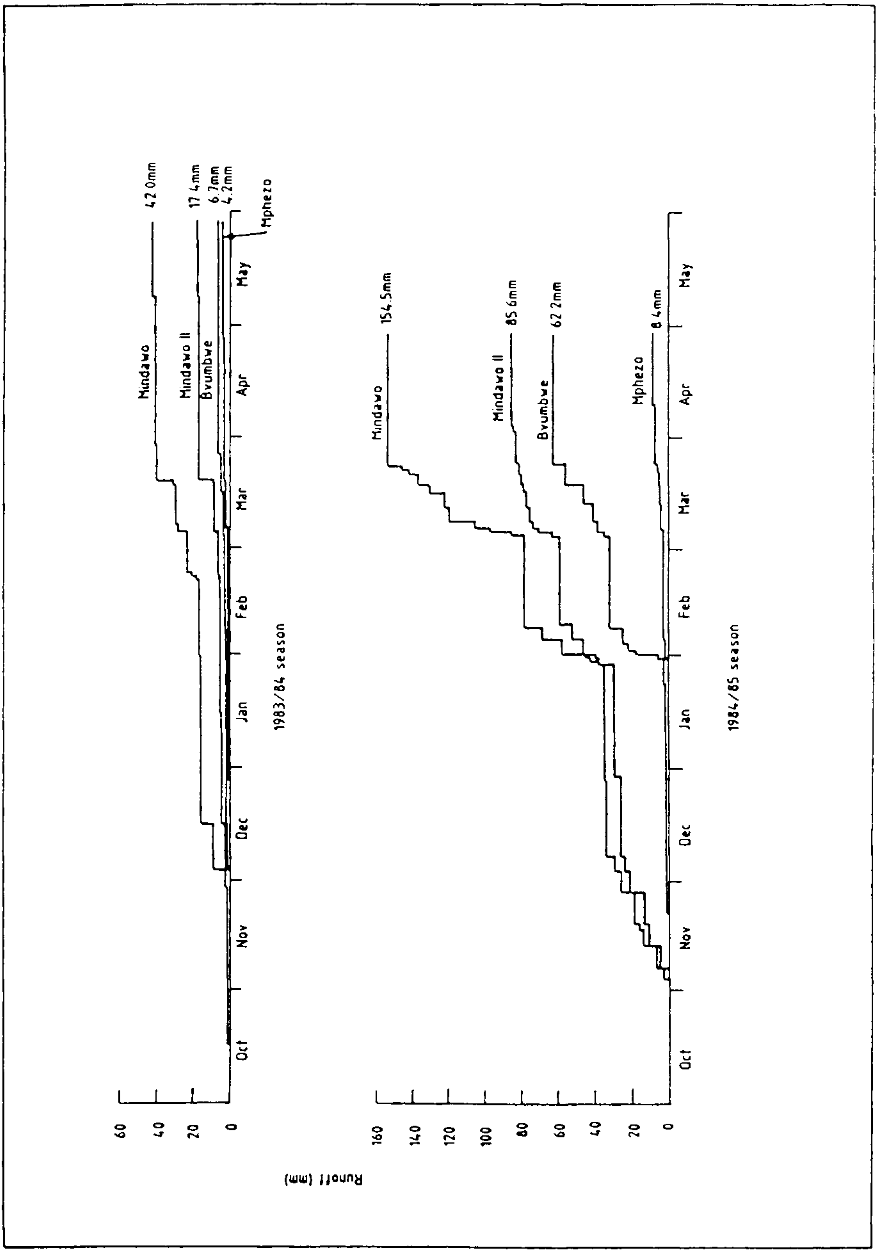


Figure 2 Cumulative runoff records for 1983/84 & 1984/85 seasons



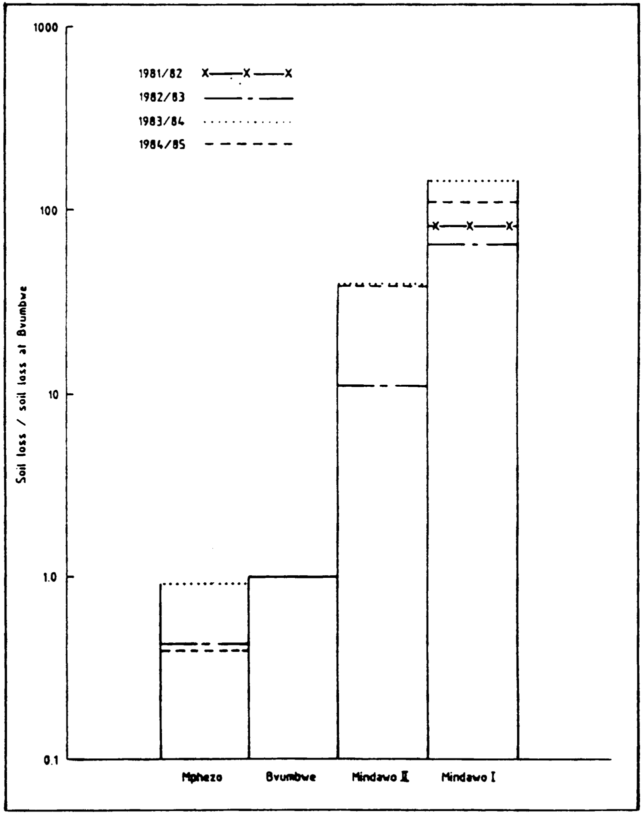


Figure 3 Ratio of soil loss to that in the Bvumbwe catchment

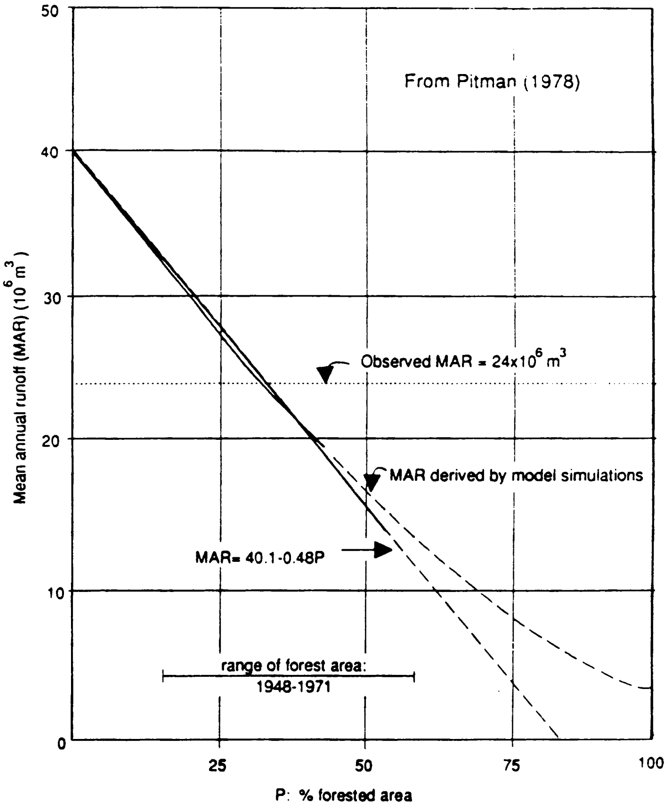


Figure 4 Relationship between mean annual runoff and forested area

Implications of changes in soil erosion rates, runoff rates, amounts and distributions

The movement of sediment downstream is highly influenced by high discharge events. This is because the relationship between suspended bed material concentration and discharge is a power law, ie:

$$\text{Concentration} = a * \text{Discharge}^{b}$$

where a and b are constants for a given river site, and b > 1.

This means that the total amount of suspended bed material transport is a power law with an exponent of b+1, ie:

$$\text{Transport} = a * \text{Discharge}^{b+1}$$

In areas where sediment supply is not restricted (ie. high erosion rates even on limited areas of the catchment, sediment deposits in the river valley, erodible river bed and banks) changes in the discharge pattern can thus have a major effect on the downstream sediment supply. Because of the form of the relationship, there is a much higher price to pay (in terms of increased sediment yield) for increased flood discharges, than any benefit that may accrue from reduced annual runoff volume. These concepts are illustrated in Figures 5 to 10.

Let us first imagine a situation where annual discharge is not greatly changed by the implementation of agroforestry, but both peak and low flows are increased. This situation was reported to have happened in the case described by Pereira in Kenya, which was previously mentioned. Figure 5 shows an idealised distribution of discharges before and after agroforestry has been developed. If we now assume a relationship of the form given above, between sediment transport and discharge, it is possible to calculate sediment yield for each group of discharges, and hence estimate annual sediment yield from the different discharge distributions. For all calculations in this paper, we will assume constant a = 0.005, and b = 2.0, values which have been found from our work in the Philippines. Figure 6 shows the

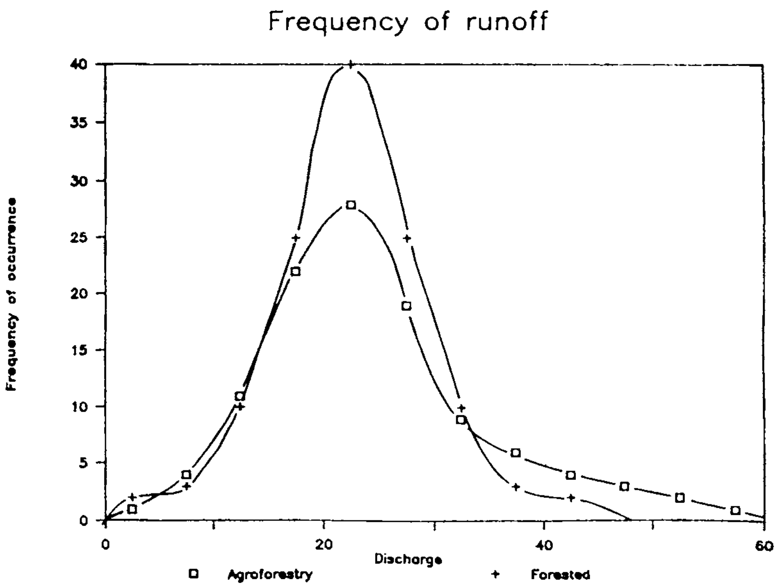


Figure 5 Hypothetical changes in runoff frequently due to land use change from forest to agroforest

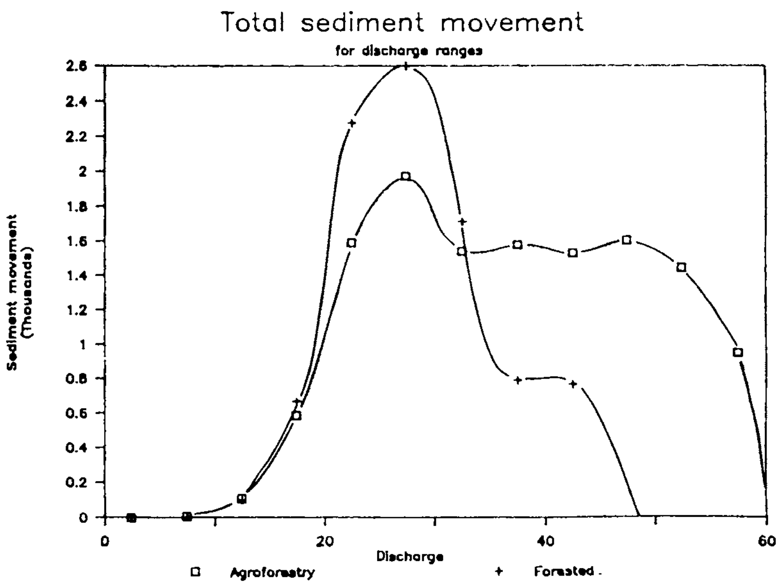


Figure 6 Changes in sediment transporting capacity due to hypothetical discharge frequency changes (forest to agroforest)

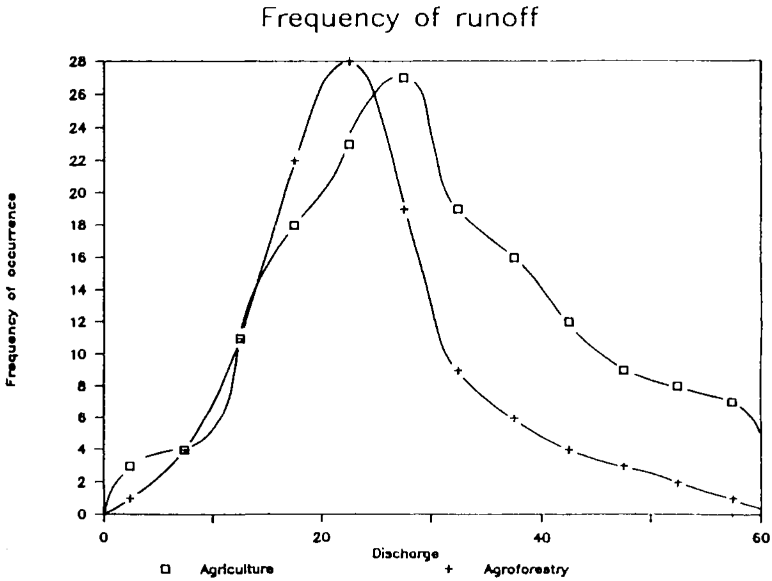


Figure 7 Hypothetical changes in runoff frequency due to land use change from agriculture to agroforest

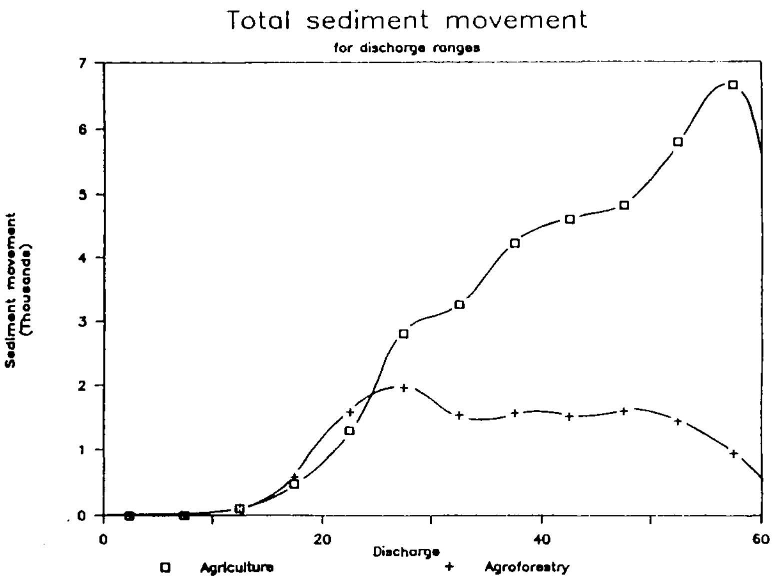


Figure 8 Changes in sediment transporting capacity due to hypothetical discharge frequency changes (agriculture to agroforest)

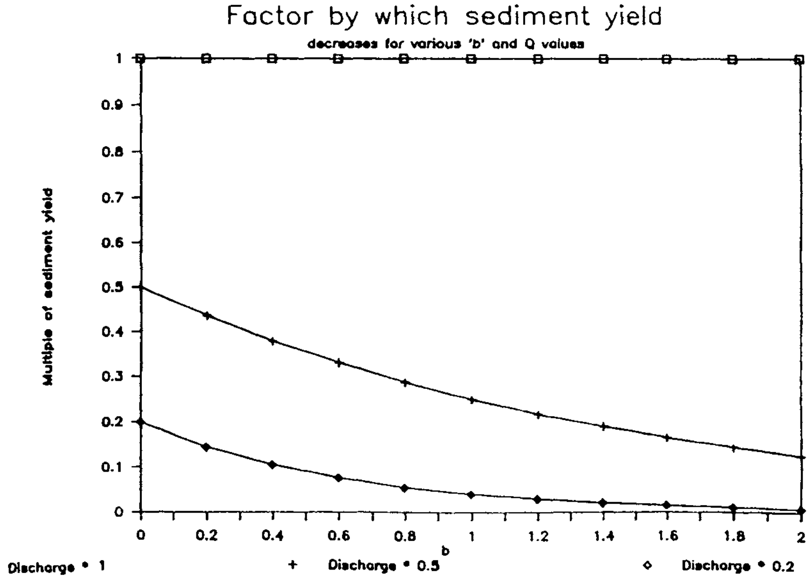


Figure 9 Potential decreases in sediment yield for reduced instantaneous discharge frequency changes

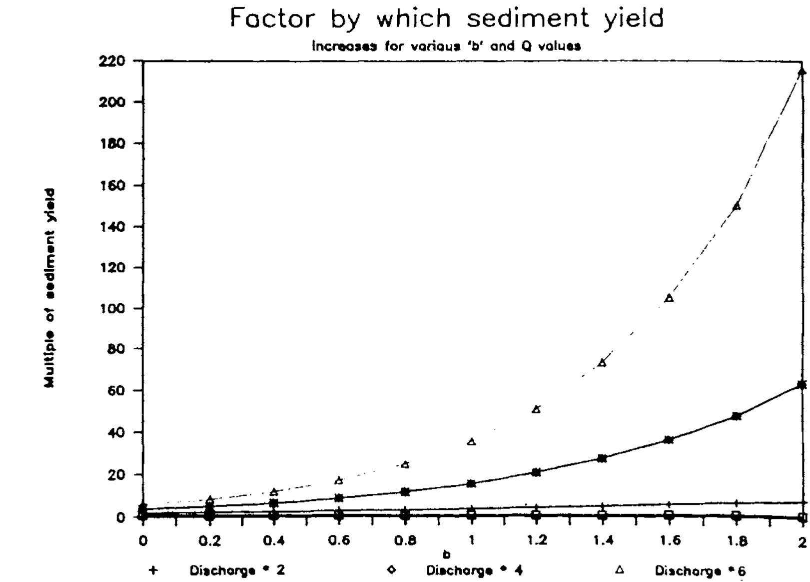


Figure 10 Potential increases in sediment yield for increased instantaneous discharge

result of these calculations in pictorial form. The data and calculations are given in Table 3.

A similar calculation can be done for a situation where peak and low flows together with annual discharge are reduced. Idealised distributions for this situation are shown in Figure 7, with corresponding sediment yields on Figure 8. These calculations are summarised in Table 4.

It can be seen from these two series of calculations, that simply shifting the distributions of discharge to higher flows, can dramatically increase sediment yield. In the first example we only increased peak discharge by 35%, without any increase in annual runoff. This caused a 45% increase in the capacity of the river to transport sediment.

If we can in some way reduce both annual discharge and peak flows, then corresponding reductions in the downstream sediment yield will result. This is what was shown by the second example, where annual discharge was reduced to 0.51 of the previous value, peak discharge was reduced by 0.79 and the sediment yield decreased to only 0.28 times its former value.

Although these examples are hypothetical, the point to bear in mind is that in terms of sediment yield, the important parameters are sediment availability and both the distribution and amount of discharge. Figures 9 and 10 show the factors by which sediment yield would be multiplied for certain values of the exponent 'b' in our power law equation and various multiples of instantaneous discharge. So for a 'b' value of 1.5, if we double the discharge for the peak flood event, the sediment yield will increase, for that storm, by a factor of 6.25. Similarly if we halve peak discharge we reduce sediment yield to 0.177 times its previous value. These calculations assume that sediment supply is not restricted. Typical values for 'b' are between 1 and 2.

A further complication is that there is some evidence that the concentration of sediment in a river may tend towards a maximum limit at extreme flows. This in part depends on sediment availability, but also on the size grading of that sediment. Any review of sediment concentrations in the major Chinese rivers will confirm that if sufficient fine material is available, then

Table 3

Flow and sediment distribution for forested catchment

Mean discharge	Number of storms	Total discharge	Sediment conc.	Sediment movement per event	Total sediment movement
2.5	2	2	0.03125	0.078125	0.15625
7.5	3	21.5	0.28125	2.109375	6.328125
12.5	10	525	0.78125	9.765625	97.65625
17.5	25	437.5	1.53125	26.79687	669.9218
22.5	40	900	2.53125	56.95312	2278.125
27.5	25	687.5	3.78125	103.9843	2599.609
32.5	10	325	5.28125	171.6406	1716.406
37.5	3	112.5	7.03125	263.6718	791.0156
42.5	2	85	9.03125	383.8281	767.6562
Totals	120	2700			8926.875

Flow and sediment distribution for catchment under agroforestry

Mean discharge	Number of storms	Total discharge	Sediment conc.	Sediment movement per event	Total sediment movement
2.5	1	2.5	0.03125	0.078125	0.078125
7.5	4	30	0.28125	2.109375	8.4375
12.5	11	137.5	0.78125	9.765625	107.4218
17.5	22	385	1.53125	26.79687	589.5312
22.5	28	630	2.53125	56.95312	1594.687
27.5	19	522.5	3.78125	103.9843	1975.703
32.5	9	292.5	5.28125	171.6406	1544.765
37.5	6	225	7.03125	263.6718	1582.031
42.5	4	170	9.03125	383.8281	1535.312
47.5	3	142.5	11.28125	535.8593	1607.578
52.5	2	105	13.78125	723.5156	1447.031
57.5	1	57.5	16.53125	950.5468	950.5468
Totals	110	2700			12943.12

Ratios for agroforestry/forestry

Annual discharge	1
Peak discharge	1.352941
Annual sediment load	1.449905

NB: For this example sediment concentration = 0.005 * Discharge^2

Table 4

Flow and sediment distribution for catchment under agricultural use

Mean discharge	Number of storms	Total discharge	Sediment conc.	Sediment movement per event	Total sediment movement
2.5	3	7.5	0.03125	0.078125	0.234375
7.5	4	30	0.28125	2.109375	8.4375
12.5	11	137.5	0.78125	9.765625	107.4218
17.5	18	315	1.53125	26.79687	482.3437
22.5	23	517.5	2.53125	56.95312	1309.921
27.5	27	742.5	3.78125	103.9843	2807.578
32.5	19	617.5	5.28125	171.6406	3261.171
37.5	16	600	7.03125	263.6718	4218.75
42.5	12	510	9.03125	383.8281	4605.937
47.5	9	427.5	11.28125	535.8593	4822.734
52.5	8	420	13.78125	723.5156	5788.125
57.5	7	402.5	16.53125	950.5468	6653.828
62.5	5	312.5	19.53125	1220.703	6103.515
67.5	3	202.5	22.78125	1537.734	4613.203
72.5	1	72.5	26.28125	1905.390	1905.390
Totals		5315			46688.59

Flow and sediment distribution for catchment under agroforestry

Mean discharge	Number of storms	Total discharge	Sediment conc.	Sediment movement per event	Total sediment movement
2.5	1	2.5	0.03125	0.078125	0.078125
7.5	4	30	0.28125	2.109375	8.4375
12.5	11	137.5	0.78125	9.765625	107.4218
17.5	22	385	1.53125	26.79687	589.5312
22.5	28	630	2.53125	56.95312	1594.687
27.5	19	522.5	3.78125	103.9843	1975.703
32.5	9	292.5	5.28125	171.6406	1544.765
37.5	6	225	7.03125	263.6718	1582.031
42.5	4	170	9.03125	383.8281	1535.312
47.5	3	142.5	11.28125	535.8593	1607.578
52.5	2	105	13.78125	723.5156	1447.031
57.5	1	57.5	16.53125	950.5468	950.5468
Totals	110	2700			12943.12

Ratios for agroforestry/agriculture

Annual discharge	0.507996
Peak discharge	0.793103
Annual sediment load	0.277222

NB: For this example sediment concentration = 0.005 * Discharge^2

the river will carry it! The tendency to a maximum sediment concentration is not seen everywhere, and so far there is no method of predicting in which rivers it will occur. To err on the side of safety, one would normally assume no concentration limit.

Increasing sediment yield to a downstream area, which by definition will have lower river channel slopes and a corresponding lower ability to transport sediment, may well cause aggradation. This may be in the river, or in downstream engineering works such as irrigation schemes or reservoirs. These all have associated management problems and costs. Aggradation in the river may well mean increased flooding and less predictable river locations. The latter makes the siting of offtakes extremely difficult, and often results in offtakes which are stranded laterally.

A decrease in sediment supply to the downstream area may well be thought of as a good thing, but it again has associated problems. If sediment supply is reduced, but discharge remains the same then it is possible that the river will begin to erode the river banks and bed in order to supply itself with sediment. This can again result in stranded irrigation or water supply offtakes, this time above the level of the river.

Changes in the discharge patterns and amounts have more obvious implications for the downstream zone. Increasing peak discharge will result in a greater risk of flooding downstream, with a lower risk of flooding being due to lower peak discharges. But lower peak flows may well go hand-in-hand with reduced low flows and annual discharge, both of which mean reduced water abstraction is possible. Reductions in low flows may even result in periods of critical water shortage for water supply or irrigation schemes.

So, the upstream-downstream relationships are not simple, and are not even reliably predictable at present. Changes in flow distributions and the assessment of sediment availability are two areas where it is particularly difficult to make reliable predictions. It is probably true to say that most downstream benefits have an associated downstream cost and vice versa. But this does not mean that they can be ignored. Much research is needed in this area, if successful development, in terms of the catchment as a whole, is to occur.

The prediction of changes in downstream discharge and sediment transport due to upstream land use change

The prediction of the hydrological effect of various conservation techniques, especially in terms of sediment yield, is something which is at present very difficult to carry out. This is particularly true in the tropics, where little data on soil loss or sediment movement downstream have been collected. There are predictive models available, both for estimating soil loss under various land uses, and for predicting sediment yield. Most of these have been developed in the USA, and are not transferable to the different climatic, topographic, soils and agricultural conditions found in the tropics. Many of the models fall down on the constituent parameters which have to be estimated en route to prediction. An example of this is the EI30 parameter representing rainfall erosivity in the Universal Soil Loss Equation (Wischmeier and Smith, 1978). It is now well reported that EI30 overestimates erosivity at the high rainfall intensities found in the tropics.

Many of the sediment yield and discharge prediction models that are available, are extremely data hungry, demanding inputs such as twenty years of continuously recorded rainfall data, or cross-sections every 100 metres down a river profile (eg. Beasley, 1977; Li, 1977; Crawford and Linsley, 1966; Holtan et al, 1975). Collection of this sort of detailed data is obviously out of the question when one is just trying to assess the impact of a small land management plan for a fraction of the catchment; realistically, it is not even going to happen for assessment of major projects. Models which do show some promise in terms of predicting the parameters of interest have rarely been tested in the tropical environment, partly because of data availability problems. Many of them are, in any case, based on the Universal Soil Loss Equation which has been shown to be lacking outside of the USA. The work of Moore and Clarke (1981 and 1983), using a statistically based runoff and sediment yield model, was tested on data from the study in Malawi, but was not very successful. This was possibly because the model was developed on data from

Europe, and did not transfer well to African conditions. It is hoped that further work to adapt the model to non-European conditions will take place.

The alternatives to these data hungry, sophisticated computer models are a few very simplistic prediction techniques, which take a limited view of the causal and restrictive factors in the runoff-erosion process (eg. Fournier, 1960; Fleming, 1969; Al Kadhimi, 1982). These models also present difficulties for inclusion of limited land use change. At best they give order of magnitude answers.

Another favoured technique for sediment yield prediction is the use of a sediment delivery ratio, in conjunction either with data or predictions of soil erosion at the small scale. There are several different versions of the sediment delivery ratio, all empirical (eg. Roehl, 1962; Williams, 1977; Renfro, 1975). Some are based on catchment area, whilst others rely on topographic relationships (Fig. 11). All of them purport to do the same thing, which is to use soil erosion figures for the whole catchment (divided into small areas and assessed individually) and then to scale these down to allow for the temporary and permanent deposition of sediment on its way downstream from the fields to the river. The basic concept is sound in that soil may be eroded many times on its way down hill, but will only once be part of the sediment yield of the catchment. However, thinking that a simple reduction factor can represent the complexity of sediment erosion and transport is not realistic, and more research is needed to better explain the processes involved. It will not be possible to model the overland sediment movement phase throughout a catchment, because of the complexity of the system. We only have to remove one tree from a hillside to alter both the local erosion and the movement of sediment which previously got stuck behind the tree! It would simply be impossible to incorporate all the detailed information that would be needed for such modelling, and even if we could it would be impossible to keep up with the changes to the system which happen every day. So, we must settle for some sort of 'lumped' approach to modelling. At Hydraulics Research (HR) we are convinced that the best way to pursue this subject is to monitor the effects of various land uses at the catchment scale, rather than on a plot

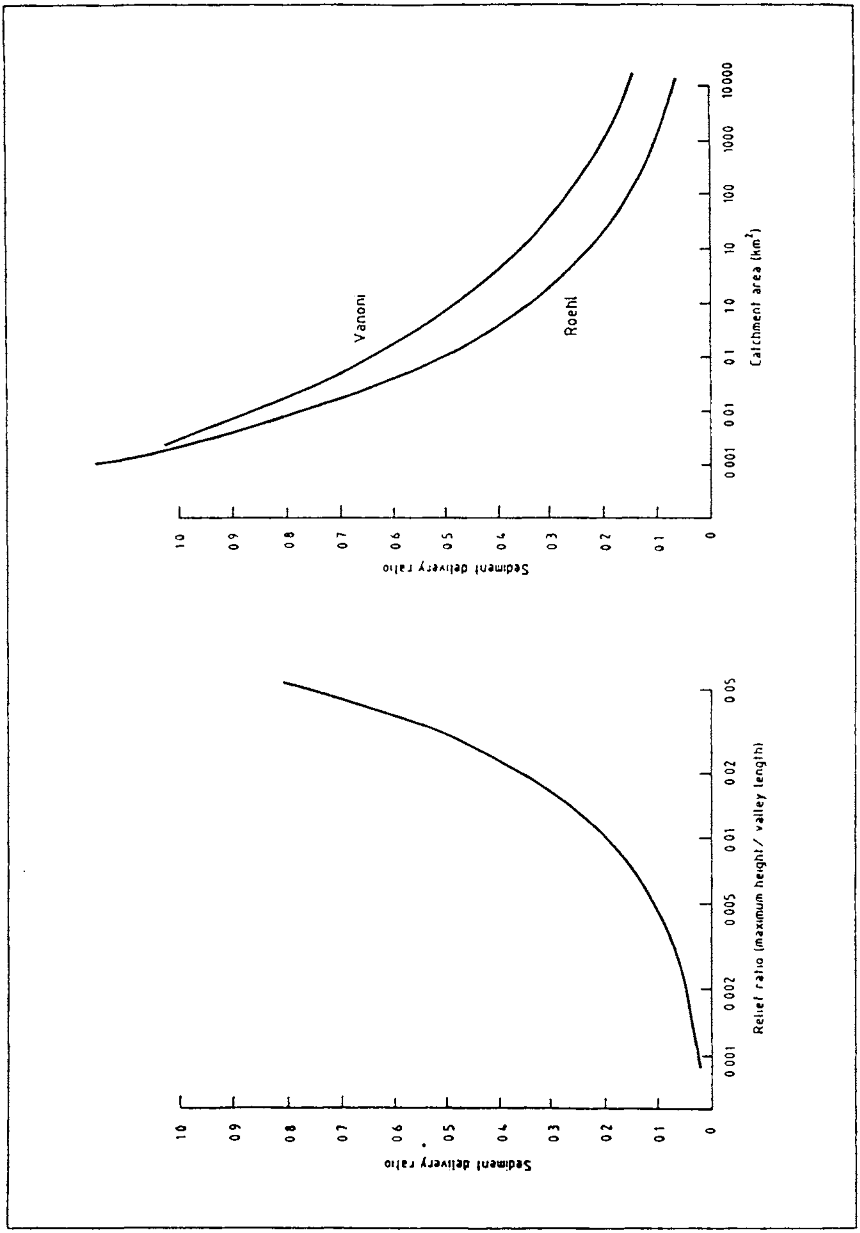


Figure 11 Sediment delivery ratio as a function of catchment area and relief ratio

scale. Plots, of course are useful for quantifying on-site benefits, but are of little use to the off-site questions.

The research of the soil erosion group of the Overseas Development Unit (ODU) at HR is focused on improving prediction techniques for sediment yield in the tropics. This involves, by default, modelling discharge patterns and soil erosion, and changes in them due to alterations in land use. At present our research is in the early stages, but we believe that we can now produce more realistic estimates of sediment yield than has previously been possible. Our approach is a modular one, looking at sediment supply, sediment transport, distributions of rainfall, runoff and flood events separately, so that different aspects can be updated or improved without changing the way that the final predictions are done. To carry out this work we must look at catchments in terms of several smaller sub-catchments which we can study in some detail, and about which we can make reasonably reliable estimates. This approach gives us the flexibility to assess the effect of changed land use on a small area of the catchment, on water or sediment yield at some point downstream.

In the meantime we are carrying out measurements at the small catchment scale (10's of hectares) (Amphlett, 1986; Amphlett and White, 1986; Dickinson, 1988) as well as at larger scales. Our major research project for the last four years has focused on the measurement of discharge and sediment transport for a 4123 square kilometre catchment in the Philippines (Amphlett et al, 1987; Wooldridge, 1986). This study is aimed at investigating the way in which sediment moves through the catchment, by monitoring at a series of nested sites, with areas increasing by a factor of 10, as one moves to the next site downstream. A similar project was initiated in Botswana (Amphlett and Hare, 1988; Blyth, 1989a). This latter project has unfortunately given little data, in part due to a one in fifty year flood which removed the bridge from which we were monitoring. We hope to find another site for a further nested catchment study shortly.

However, the monitoring of discharge and sediment yield forms but a part of the work that is needed on the prediction of catchment sediment yield in the tropics. A further part of our study has been aimed at learning from the data, and developing predictive techniques which address both the lack of models available for the tropics, and the need to assess the catchment implications of changes in land use at whatever scale. The basic concept was to look at a catchment in terms of several small sub-catchments. This is partly because much more work has been done at the smaller scale, both in terms of monitoring and predictive techniques, and we thus feel more confident about estimating sediment yield at the small scale. The use of small catchments also limits the variability of soils, land use and rainfall within the area which we are considering as a unit in terms of sediment yield. Each of our sub-catchments has a defined stream outlet, meaning that from the outlet of the sub-catchments downstream we are routing discharge and sediment in a river rather than overland. We are thus detaching the two processes which the sediment delivery ratio inherently considers together, namely overland flow and river discharge routing. The desirability of this split has long been recognised (Pacific Southwest Interagency Committee, 1968; Walling and Webb, 1983, Fleming, 1984) and is incorporated in some of the more sophisticated predictive models.

The estimation of sediment yield at the small-scale is done by use of an erosion prediction technique in combination with a sediment delivery parameter to represent the amount of eroded sediment which reaches the stream. This means that we must consider erosion from areas even smaller than the sub-catchments. This is achieved by use of a micro-computer based Geographical Information System. Variation of parameters is considered for each pixel of the catchment. The area which a pixel represents depends on the scale at which one works. For our 4123 square kilometre catchment each pixel represents an area of approximately 150x150 metres. This enables realistic application of the field or plot scale erosion predictors. We have so far used the SLEMSA (Soil Loss Estimator for Southern Africa, Elwell (1980)) in combination with a sediment delivery factor due to Hession and Shanholtz (1988). This work is reported in White (1989a). We are going on to test both modified versions of the Universal Soil Loss Equation, and the AGNPS model (Hession and Young, 1988).

Potential erosion can be calculated for each pixel throughout the catchment in much the same way recommended by Stocking (1987).

This goes on to be lumped together on a sub-catchment basis to give a figure for sediment yield. For the Philippines project we can obviously compare the output from our model with the measurements we are making in the river network. It is almost certain that some degree of calibration against measurements will be necessary. This is likely to always be the case, and our recommendations for sediment yield prediction will therefore always include a limited monitoring programme.

A limited set of measurements is unlikely to cover the full range of events that may occur at a site, and so some way of putting the period of measurement into context in the long term is needed. This forms the third aspect of our study, which looks at statistical distributions of rainfall and runoff events, changes in land use that have happened or may occur in future, and any other factors which have implications for change in the rainfall, runoff or sediment supply patterns (Blyth, 1989b).

Table 5

Multiples of sediment movement caused by variation in discharge

Sediment concentration = a * Discharge^b

Peak discharge *	0.2	0.5	1	2	4	6
Value of b	Factor by which sediment yield increases or decreases					
0	0.2	0.5	1	2	4	6
0.2	0.144955	0.435275	1	2.297396	5.278031	8.585814
0.4	0.105061	0.378929	1	2.639015	6.964404	12.28603
0.6	0.076146	0.329876	1	3.031433	9.189586	17.58093
0.8	0.055189	0.287174	1	3.482202	12.12573	25.15777
1	0.04	0.25	1	4	16	36
1.2	0.028991	0.217637	1	4.594793	21.11212	51.51488
1.4	0.021012	0.189464	1	5.278031	27.85761	73.71621
1.6	0.015229	0.164938	1	6.062866	36.75834	105.4856
1.8	0.011037	0.143587	1	6.964404	48.50293	150.9466
2	0.008	0.125	1	8	64	216

Research needs

It is apparent from what has been reported here that there is much work to do on the prediction of the downstream effects of upstream land use change, particularly in the tropics. It is not even easy to model a catchment with no land use change - but at least then we have the option of measurement! These shortcomings in modelling are not specific to agroforestry, although the lack of data on the on-site effects of agroforestry do not ease the situation. Research needs are therefore twofold.

First there is a need for more data on the effect of agroforestry on soil erosion and runoff amounts and distributions. This is of course not a simple task, as the term agroforestry covers such a wide range of cropping patterns and management techniques. It is therefore vital that where measurements do occur, they, and the agroforestry system to which they apply, must be comprehensively reported. Furthermore, these data must be made available. It is surprising how much measurement of erosion rates is done and then not reported outside of the organisation where it was carried out. Measurements on the implications of agroforestry need to be done at both plot and small catchment scales. As stated before the plot studies are not of much use for catchment scale prediction, although being useful for on-site assessment.

The second research area which needs to be further investigated is the movement of sediment and water through the catchment. This is where our work at HR is concentrated, although as part of this work we are monitoring at the small catchment scale. We think this is best done by measurement in a series of nested catchments, whilst at the same time some fundamental thinking about sediment delivery is done. The latter has commenced at HR with some ideas, and order of magnitude calculations for a cyclone affected area such as the Philippines (White, 1989b).

Apart from the technical questions, we feel that some thought must be given to the economic analysis of land management plans. Often the implications of such projects are far reaching and long lasting, with some benefits or costs not happening for several years. With current cost-benefit analysis and existing discounting rates, benefits 20 to 25 years in the future are of virtually no value. Of course any change in economic analysis is dependent on reliable technical predictions being made, so it makes sense to work together in a multi-disciplinary team - something which happens infrequently today, but which would seem to be vital for future progress.

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