Chapter 10
Plant Nutrients

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

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

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

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

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

Nitrogen fixation by trees and shrubs

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

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

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

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

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

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

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

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

Species	N fixation (kgN/ha/yr)	Source
Acacia albida	20	Nair (1984)
Acacia mearnsii	200	Dommergues (1987)
Allocasuarina littoralis	220 (?)	Dommergues (1987)
Casuarina equisetifolia	60–110	Dommergues (1987)
Coffee + *Inga* spp.	35	Roskoski & van Kessel (1985)
Coriaria arborea	190	Dommergues (1987)
Erythrina poeppigiana	60	Dommergues (1987)
Gliricidia sepium	13	Dommergues (1987)
Inga jinicuil	35–40	Dommergues (1987)
Inga jinicuil	50	Roskoski (1982)
Inga jinicuil	35	Roskoski & van Kessel (1985)
Leucaena leucocephala	100–500	Dommergues (1987)
Leucaena leucocephala (in hedgerow intercropping)	75–120	Mulongoy (1986)
Leucaena leucocephala	100–130(6 months)	Sanginga et al. (1987)
Prosopis glandulosa	25–30	Rundel et al. (1982)
Prosopis glandulosa	40–50	Virginia (1986)
Prosopis tamarugo	200	Nair (1984)
Rain forest fallow	40–100	Greenland (1985)
Mature rain forest	16	Jordan et al. (1982)

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

Nutrient cycling in agroforestry systems

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

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

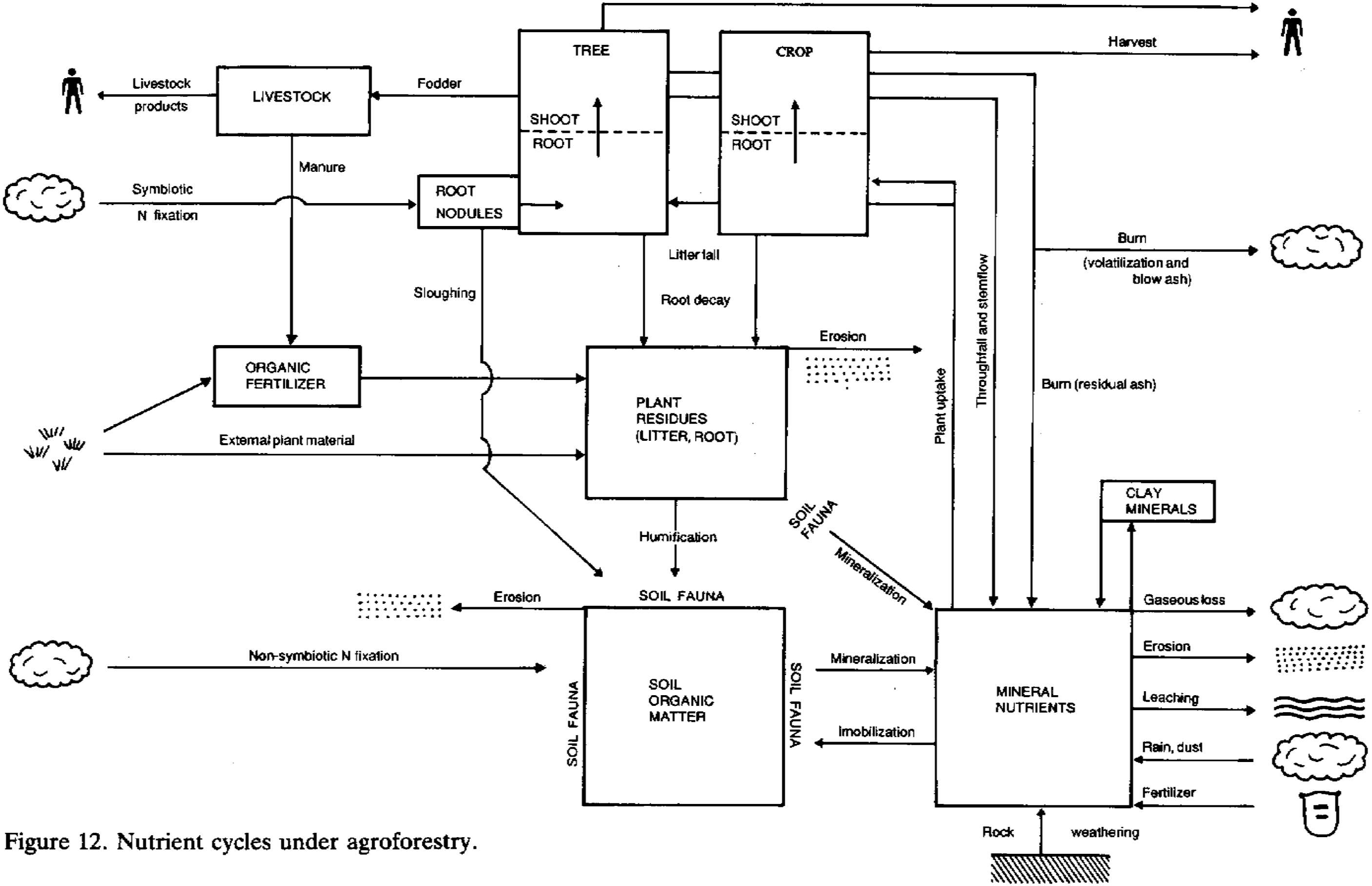

Figure 12. Nutrient cycles under agroforestry.

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

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

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

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

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

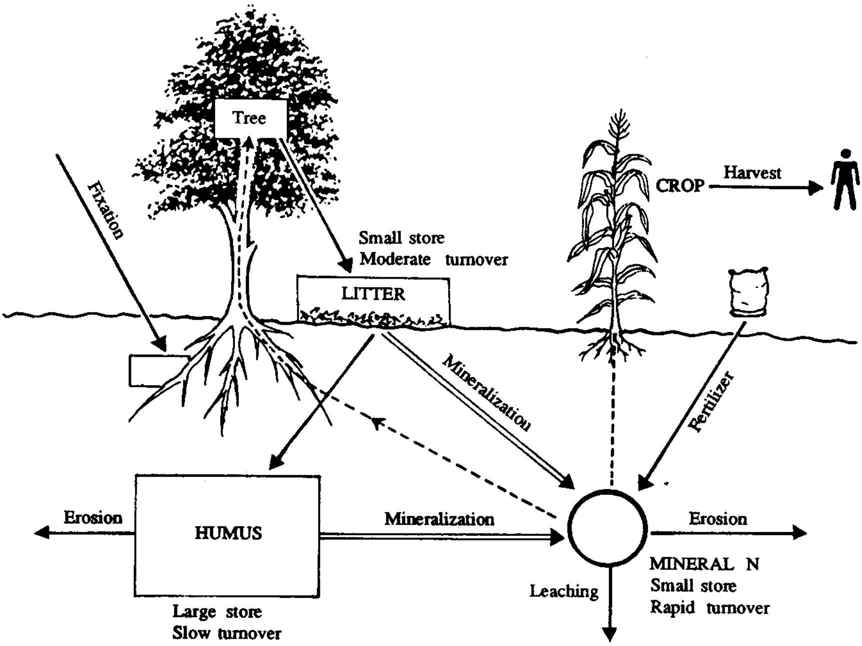

Figure 13. The nitrogen cycle under agroforestry, simplified to show major stores and flows.

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

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

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

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

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

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

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

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

Examples

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

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

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

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

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

Table 23 (cont)

Tree	Nitrogen	Phosphorus	Potassium	Calcium	Source
Gliricidia sepium	PR4.40	PR0.26	PR2.81		Yamoah et al. (1986)
Gmelina arborea	L2.07, W0.22	L0.23, W0.03	L1.16, W0.37	L0.57, W0.19	Chijoke (1980)
Inga sp.	L1.61, W2.28				Aranguren et al. (1982)
Leucaena leucocephala	L4.2	L0.2			Agboola (1982)
Leucaena leucocephala	L2.51				Buck (1986)
Leucaena leucocephala	L4.33	L0.28	L2.50	L1.49	Kang et al. (1984)
Leucaena leucocephala		PR0.3	PR1.0	PR2.5, L3.0	Akbar & Gupta (1984)
Leucaena leucocephala	PR2.53				Kang et al. (1985)
Leucaena leucocephala	L4.33	L0.28	L2.50	L1.49	Wilson and Kang (1986)
Leucaena leucocephala	L4.0				BOSTID (1984)
Leucaena leucocephala	L3.15, BR0.41	L0.15, BR0.053	L1.38, BR0.34	L1.02, BR0.39	Lulandala (in press)
Prosopis glandulosa	L2.8,W0.7				Rundel et al. (1982)
Sesbania grandiflora	L3.36–3.64				Ghai et al. (1985)
Sesbania sesban	L2.43–4.36				Ghai et al. (1985)
Tephrosia candida	L3.8		L0.2		Agboola (1982)

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

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

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

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

Cacao-*Cordia*: 115 kg N/ha/yr of which 71 from *Cordia*
14 kg P/ha/yr of which 6 from *Cordia*
65 kg K/ha/yr of which 35 from *Cordia*
Cacao-*Erythrina*: 175 kg N/ha/yr of which 122 from *Erythrina*
9 kg P/ha/yr of which 7 from *Erythrina*
54 kg K/ha/yr of which 27 from *Erythrina*
(Alpizar et al., 1986, 1988).

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

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

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

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

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

Country and climate	Land use	Nitrogen (kg/ha/yr)	Source
Nigeria, subhumid	Hedgerow intercropping, 4 m rows, prunings:		Kang & Bahiru Duguma (1985)
	Leucaena leucocephala	200	
	Gliricidia sepium	100	
Nigeria, subhumid	Hedgerow intercropping, 2 m rows, prunings:		Bahiru Duguma et al. (1988)
	Leucaena leucocephala	150–280	
	Gliricidia sepium (6 months)	160–200	
	Sesbania grandiflora (6 months)	50–100	
Venezuela, subhumid	Coffee-*Erythrina-Inga* unfertilized:		Aranguren et al. (1982)
	trees only	86	
	trees + coffee	172	
	Cacao-*Erythrina-Inga*		Aranguren et al. (1982)
	trees only	175	
	trees + cacao	321	
Costa Rica, humid	Cacao-*Cordia alliodora* (fertilized)	115	Alpizar et al. (1986, 1988)
	Cacao-*Erythrina poeppigiana* (fertilized)	175	
Various, humid	Rain forest	60–220	Bartholemew (1977)
Various, humid	*Leucaena leucocephala*, plantation:		BOSTID (1984)
	foliage	500–600	
	litter fall	100	
18 sites, humid	Forest	mean 134	Lundgren (1978)
Ivory Coast, humid	Rain forest	113,170	Bernhard-Reversat (1977)
Brazil, humid	Rain forest	61	Jordan et al. (1982)
USA: California, arid	*Prosopis glandulosa* (woodland)	45	Rundel et al. (1982)

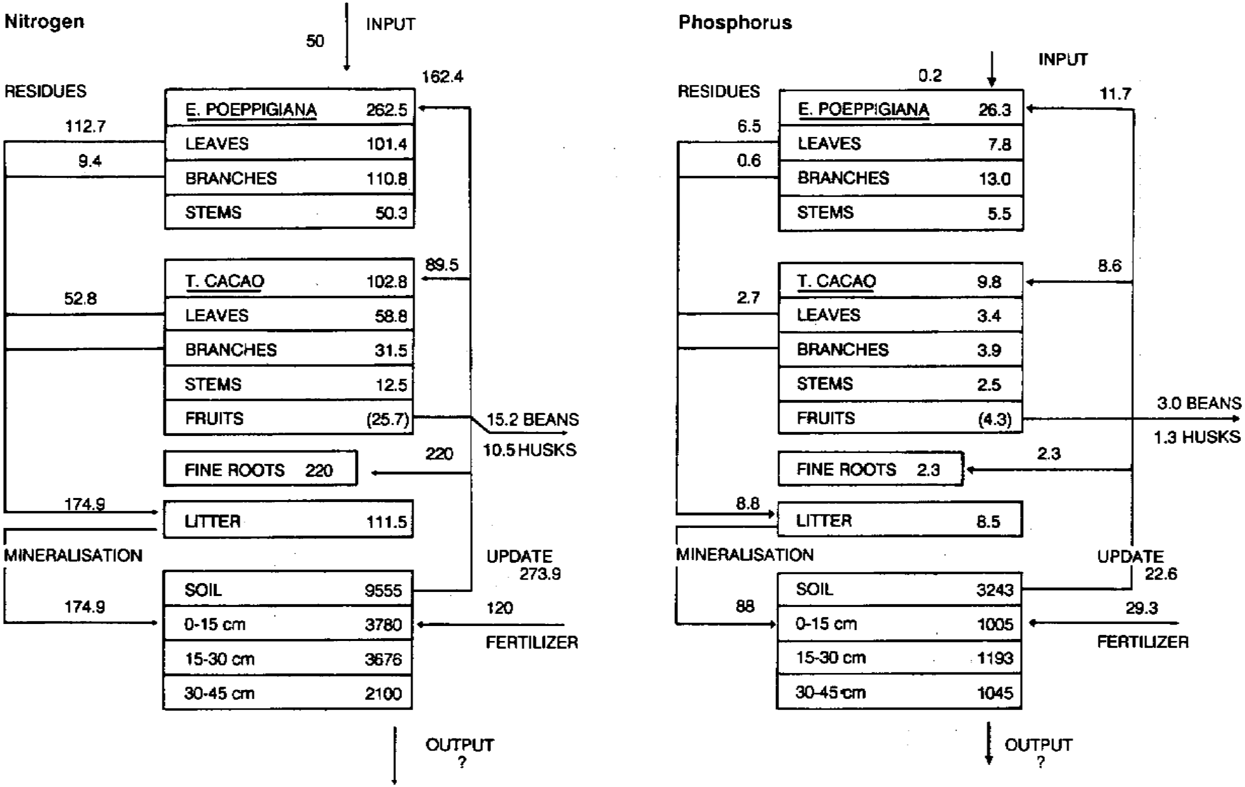


Figure 14. Nitrogen and phosphorus cycling under a coffee-*Erythrina-Inga* system in Costa Rica (Alpizar et al., 1986, 1988).

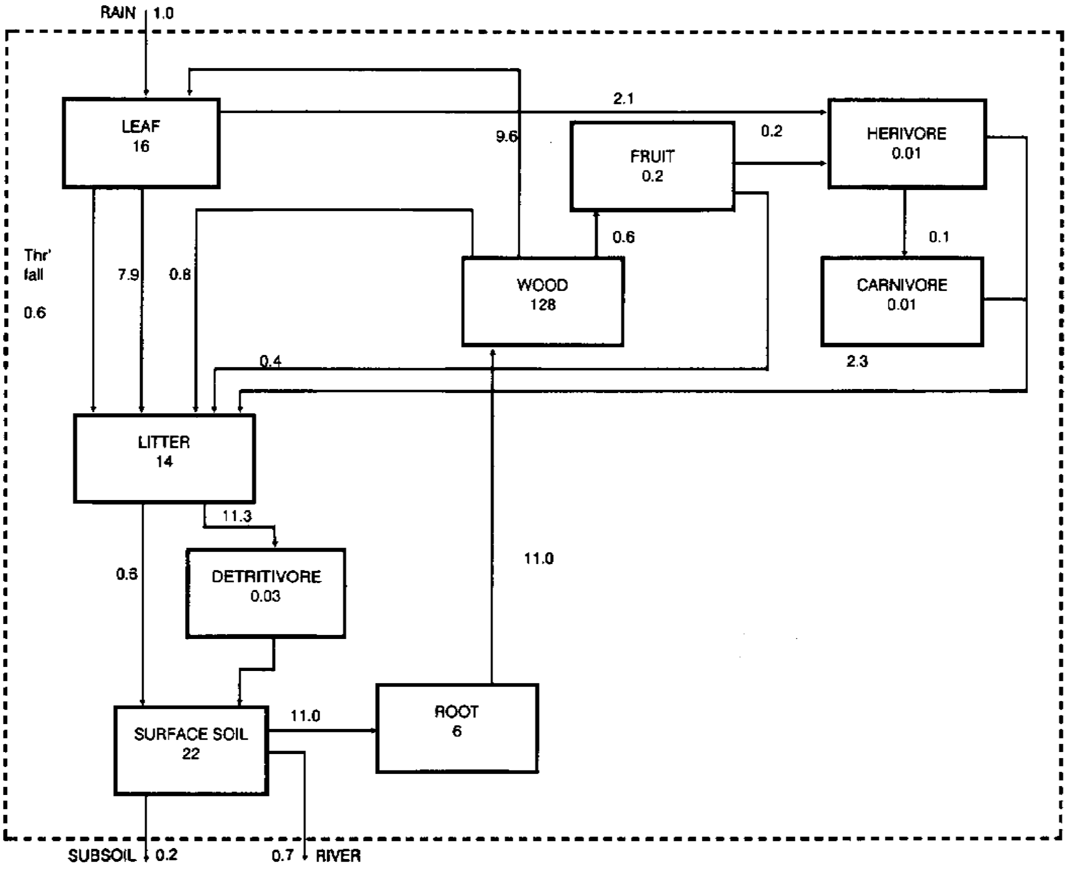


Figure 15. The phosphorus cycle under rain forest, Panama (after Golley et al., 1975).

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

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

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

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

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

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

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

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

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

Chapter 11

Other Soil Properties and Processes

Soil physical properties

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

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

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

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

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

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

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

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

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

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

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

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

Acidity

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

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

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

Thus there are two distinct problems:

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

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

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

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

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

This may be compared with a tree biomass production of 10 000 kg DM/ha/yr, typical for the moist savanna zone, and a mean tissue calcium content of 1% (higher for leaves, lower for other parts). This gives an accumulation of calcium, in a complete tree cover, of 100 kg Ca/ha/yr, equivalent to 250 kg $CaCO_3$ or somewhat more of lime fertilizer. This is only one twentieth of a typical lime requirement. In many agroforestry systems, notably hedgerow intercropping, the tree cover is well below 100%. Moreover, the bases contained in the litter have necessarily been extracted from the soil.

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

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

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

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

Vegetation clearance and burning

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

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

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

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

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

Erosion control and soil fertility

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

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

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

Chapter 12

The Role of Roots

Root biomass, turnover and nutrient content

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

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

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

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

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

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

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

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

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

Percentage of plant biomass nutrients in root system

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

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

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

Mycorrhizae

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

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

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

Root competition for nutrients

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

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

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

$$r = 1/(\pi.Lv)^{0.5}$$

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

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

Roots and soil fertility under agroforestry

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

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

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

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

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

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

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

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

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

	Agricultural systems			Forest systems		Agroforestry systems			
	Young maize	Mature maize	Sweet potato	*Gmelina* plantation	Secondary forest	Coffee *Erythrina*	Cacao-*Cordia*	Tree garden	Planted fallow
Leaf biomass	330	1000	1070	3120	3070	2720	2040	2450	2480
Root biomass (to 25 cm)	390	1150	410	1280	2170	2350	2720	3070	4220
Ratio: roots-leaves	1.18	1.15	0.38	0.41	0.71	0.86	1.33	1.25	1.70

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

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

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

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

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

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

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

Chapter 13

Trees and Shrubs for Soil Improvement

What makes a good soil-improving tree?

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

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

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

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

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

PROPERTIES OF TREES WHICH FAVOUR SOIL IMPROVEMENT

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

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

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

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

Notes on trees and shrubs

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

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

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

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

Table 27 (cont)

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

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

Acacia albida
Acacia tortilis
Calliandra calothyrsus
Casuarina equisetifolia
Erythrina poeppigiana
Gliricidia sepium
Inga jinicuil
Leucaena leucocephala
Prosopis cineraria
Sesbania sesban.

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

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

Acacia

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

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

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

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

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

Alnus

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

Azadirachta

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

Bamboo

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

Cajanus

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

Calliandra

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

Cassia

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

Casuarina

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

Cordia

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

Erythrina

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

Eucalyptus

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

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

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

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

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

Gliricidia

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

Gmelina

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

Grevillea

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

Inga

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

Leucaena

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

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

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

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

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

Parkia

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

Paulownia

Paulownia elongata has been described as 'China's wonder tree'. It is grown in temperate subhumid climates (latitude 30 to 40°N). With trees spaced at 5 × 10 m, yields of intercropped wheat are as high as on land without trees, and at 5 × 20–40 m spacing, 7–10% higher. The root system is deep, mainly below 40 cm (Chin Saik Yoon and Toomey, 1986; Zhao Hua Zhu, in press).

Prosopis

Prosopis cineraria is a tree of the semi-arid to dry subhumid zones, valued in India for a variety of uses, amongst which is its effect on soil fertility. It can lay claim to being the subject of the earliest publications on agroforestry, for 'Indian scriptures are replete with a variety of references on khejri'. Its reputed effects on fertility extend beyond soils to livestock and humans!

Growth of both pastures and crops are reported as equal or better under *Prosopis* than on adjacent land. It outperforms other species in the same area in this respect. Soil nutrient content is higher beneath the trees than on adjacent open land (Table 13). There is also an improvement in organic matter, soil physical conditions and water-holding capacity (Aggarwal, 1980; Mann and Saxena, 1980).

Prosopis juliflora does not appear to equal *P. cineraria* in soil improvement, but has a high litter production and has been successfully used for reclamation of eroded land. It may, however, be competitive with adjacent crops.

Some *Prosopis* species have a remarkable capacity for biomass production and nitrogen fixation under extreme heat and drought stress. In the Sonoran Desert of California (US), a soil content of 10 200 kg N/ha under the tree canopy, compared with 1600 outside, has been recorded (Rundel et al., 1982; Felker et al., 1983).

Robinia

Robinia pseudoacacia (black locust) is a nitrogen-fixing tree that is excellent for reclamation of eroded land and soil stabilization on steep slopes.

Sesbania

At least four *Sesbania* species are employed in agroforestry, both traditional and modern. In western Kenya, *S. sesban* is planted among crops, and there are qualitative observations of equal or greater yields beneath. *S. rostrata*, besides root nodulation, is unique for its profuse stem nodulation, with 4000 to 5000 nodules on a 3-m stem (International Institute of Tropical Agriculture (IITA), 1983), making it a promising species for hedgerow intercropping.

Both *S. rostrata* and *S. bispinosa* are tolerant of waterlogging, and so can be employed in association with swamp rice cultivation, either planted along bunds or as a short fallow crop (Tran Van Nao, 1983; Bhardwaj and Dev, 1985).

Zizyphus

Like *Prosopis*, this shrub of the semi-arid zone is mentioned in Indian scriptures. It is valued particularly as fodder. A monograph by Mann and Saxena (1981) on *Z. nummularia* does not specifically mention soil fertility. However, foliage analyses show a quite high and balanced nutrient content which, coupled with its deep rooting habit, could make it a potentially useful species from a soil-fertility viewpoint if not harvested for fodder.

Chapter 14
Agroforestry Practices for Soil Fertility

The analytical approach to soil fertility under agroforestry adopted in Chapters 8 to 13 is only a means to an end. What matters are the effects of agroforestry systems as a whole upon soil properties, and thereby the sustainability of those systems.

It should be said at the outset that there are very few studies yet available which cover nutrient cycling and/or soil monitoring under agroforestry systems linked with control plots under agriculture. The main groups of work to date are the experimental studies of hedgerow intercropping conducted at IITA in Ibadan, Nigeria, and the nutrient-cycling studies carried out on plantation crop combinations in Costa Rica and other Central American countries. Apart from these, results are sparse. The few trials for which data are available are mostly at an early stage and, because of soil microvariability results, are usually not statistically significant.

This situation could change markedly in five to seven years' time. A large number of agroforestry system trials have recently been started or are planned to commence, in which it is to be hoped that nutrient cycling and soil monitoring will be carried out.

Hence the following notes necessarily contain many statements which are qualitative, or plausible hypotheses. Some are sufficiently well established for the practices concerned to be adopted by farmers, but rather few have been demonstrated by accepted standards of scientific proof.

Soil-fertility aspects of indigenous agroforestry systems

A starting point is to consider the role of soil fertility in indigenous agroforestry systems. The ICRAF Agroforestry Systems Inventory contains records of some 200 systems, of which 26 have so far appeared as published full descriptions (Nair,1984–88, 1987b, 1989).

The descriptions are listed in Table 28, with the practices that occur classified according to Table 4. They are not the result of a sampling procedure, but the balance of practices is nevertheless of interest.

Of the 42 examples of practices, 30 have a spatial-mixed arrangement of the tree component, or over 70% of the total, compared with 6 examples, or 15%, that have a spatial-zoned arrangement. The most widely

Table 28. *Soil aspects of indigenous agroforestry systems. Based on the ICRAF Agroforestry Systems Inventory (Nair, 1989). For soil aspects, small letters indicate brief mention only. For references, see Agroforestry System Descriptions (AFSD) 1–26 in the ICRAF Publications List.*

AFSD number	Country	Agroforestry practices	Components	Arrangement	Soil aspects
1,3	Tanzania	Home gardens	AS	SM	F
2	Thailand	Taungya	AS	R	a
4	Nepal	Trees for soil conservation on terraces;	AS	SZ	E
		boundary planting	AS	SZ	F,R
5	Paraguay	Trees on cropland	AS	SM	
6	Papua New Guinea	Plantation crop combinations	AS	SM	
7	Sri Lanka	Plantation crop combinations	AS	SM	e
8	Brazil	Plantation crops with pastures	SP	SM	
9	Papua New Guinea	Improved fallow;	AS	R	f
		plantation crop combinations	AS	SM	
10	Venezuela	Plantation crop combinations;	AS	SM	
		trees on pastures	SP	SM	
11	Brazil	Trees on cropland;	AS	SM	e,f
		trees on pastures	AS	SM	
12	South Pacific Islands	Plantation crop combinations;	AS	SM	
		improved fallow;	AS	R	
		plantation crops with pastures;	SP	SM	
		home gardens	AS	SM	
13	Brazil	Plantation crop combinations	AS	SM	
14	Malaysia	Plantation crops with pastures	SP	SM	f

Table 28 (cont)

AFSD number	Country	Agroforestry practices	Components	Arrangement	Soil aspects
15	India (Tamil Nadu)	Trees on cropland;	AS	SM	F,R
		boundary planting;	AS	SZ	
		windbreaks	AS	SZ	
16	Sudan	Trees on cropland;	AS	SM	f
		trees on pastures	SP	SM	
17	Ethiopia	Trees on cropland	AS	SM	F
18	India (Kerala)	Home gardens	ASP	SM	f
19	Rwanda	Trees on cropland;	AS	SM	E,F
		boundary planting;	AS	SZ	
		home gardens;	AS	SM	
		multipurpose woodlots;	T		
		(plus improved fallow, hedgerow intercropping on trial basis)			
20	Kenya	Taungya	AS	R	
21	Indonesia (Sumatra)	Multistorey tree gardens	AS	SM	E,F
22	India (north-west)	Trees on cropland;	AS	SM	E,F,R
		trees on pastures;	SP	SM	
		windbreaks;	AS	SZ	
		reclamation	T		
23	Sri Lanka	Home gardens	AS	SM	e
24	Nigeria	Home gardens	ASP	SM	F
25	Bangladesh	Home gardens	AS	SM	
26	Spain	Trees and pastures	ASP	SM	F

Note: Components: AS = agrosylvicultural, SP = sylvopastoral, ASP = agrosylvopastoral, T = trees predominant; Arrangements: R = rotational, SM = spatial mixed, SZ = spatial zoned; Soil aspects: E,e = erosion control, F,f = fertility, R,r = reclamation or use of poor soils, A,a = adverse effects.

represented practices are tree gardens (9), trees on cropland (7) and plantation crop combinations (6), followed by two sylvopastoral practices, trees on pastures (5) and plantation crops with pastures (3). The leading spatial-zoned system is boundary planting (3). It seems that farmers, unlike scientists, prefer their trees to be randomly spaced!

The last column shows the degree of emphasis on soils aspects, as E, e = erosion control, F, f = soil fertility, and R, r = reclamation or use of poor soils. Lower-case letters denote a brief mention, capitals indicate that the aspect is described as a feature of importance.

Seventeen descriptions refer to favourable effects upon soils, of which 10 describe this as an important feature; for fertility alone, the corresponding figures are 16 and 9. Only one description refers to adverse effects on soils, a statement that tree-crop competition for soil resources contributed to crop-yield decline under taungya in Thailand.

It can be concluded that, for all the lack of 'scientific proof', maintenance of soil fertility is an identified feature of a substantial proportion of indigenous agroforestry systems.

INDIGENOUS AGROFORESTRY SYSTEMS

The majority of indigenous agroforestry systems are either rotational, as in shifting cultivation, or of the spatial-mixed type. This contrasts with the spatial-zoned arrangements frequently favoured in on-station experimental work. There is food for thought in this situation.

Maintenance of soil fertility is a feature of most indigenous agroforestry systems and is recognized to be so by the farmers.

Soil-productivity aspects of eight practices have previously been reviewed by Nair (1984): shifting cultivation, planted tree fallow, taungya, trees on cropland, plantation crop combinations, hedgerow intercropping, trees for soil conservation and windbreaks, with shorter notes on some other practices. A review of South American agroforestry systems, with discussion of soil fertility, is given by Hecht (1982).

Soil fertility under specific agroforestry practices

Rotational practices

Shifting cultivation. This is the earliest and still the most widespread practice of agroforestry. There have been many case studies and reviews of the restoration of soil fertility by natural fallows, classics among which are studies based on forest in Zaire (Bartholemew et al., 1953) and the forest and savanna zones of West Africa (Greenland and Nye, 1959; Nye and

Greenland, 1960). An FAO (1974) symposium is also of particular value. For data on soil changes, some notable recent studies are:

North-east India	Ramakrishnan and Toky (1981) Mishra and Ramakrishnan (1983) Toky and Ramakrishnan (1983)
Nitrogen cycling, 4 sites	Gliessman et al. (1982)
Three Asian sites	Andriesse (1987) Andriesse et al. (1984, 1987)
Thailand	Kyuma et al. (1985)
Zambia, *Chitemene* in the savanna zone	Stromgaard (1984, 1985)
Peru	Szott et al. (1987c)

The basic findings are well known. Shifting cultivation is a sustainable system, provided that the fallow is long enough to restore soil conditions to the same state as in previous cultivation-fallow cycles. The relative lengths of cultivation and fallow are expressed as the R factor, and for any given combination of climate and soil there is a critical level for the ratio of cultivation to fallow, the soil rest-period requirement (Table 12, p. 87). If the actual R value rises above the rest-period requirement, soil degradation occurs, becoming progressively worse in successive cycles. Estimates of the rest-period requirement under low-input systems of agriculture are high, such as to make the continuation of shifting cultivation by traditional methods unrealistic under modern ratios of population to land. Savanna vegetation is less efficient at restoring fertility than forest.

The cycle of soil changes was formerly thought of as a progressive build-up of soil organic matter and nutrients during the fallow, corresponding to the increase in forest biomass. This is correct for carbon and nitrogen, but for other nutrients much of the increase goes into the vegetation and is only released to the soil upon clearance and burning. One study found that nitrogen did not decrease during cultivation, a result attributed to release through decomposition of residual tree trunks (Jordan et al., 1983).

In Thailand, soil carbon, nitrogen and phosphorus were found to reach their lowest levels three to four years after the beginning of fallows (Nakano and Syahbuddin, in press). When the same methods were applied to three south-east Asian sites with annual rainfall of 900–1200, 1560 and 4000 mm, considerable differences in nutrient-recycling mechanisms were found (Andriesse et al., 1984, 1987; Andriesse, 1987). We are far from knowing all the answers about traditional shifting cultivation.

The effects on soil properties of methods of vegetation clearance and burning have been noted (p. 148). The key features are that burning is effective in producing a rapid release of nutrients when required; but is inefficient in terms of the loss of nitrogen and plant carbon.

An early attempt at improving shifting cultivation was the corridor system, in which the fallow is still natural forest regeneration, but the area cleared for cultivation is a belt along the contour, moving up the slope in successive years to produce contour-aligned belts of forest at different stages of regeneration (Jurion and Henry, 1969). Whilst achieving erosion control, this does not in itself change the rest period requirement and thus the sustainable population:land ratio. More radical attempts to improve shifting cultivation take it into the class of improved tree fallow.

Improved tree fallow. Reasons for using a rotation of crops with planted trees, in place of colonization by natural vegetation, may be to obtain harvested products from the trees, improve the rate of soil amelioration, or both. To the extent that parts of the tree are harvested, as forage or fuelwood, the capacity for soil improvement will be reduced. The length of planned fallows was first discussed by Ahn (1979).

Long rotations of this kind are uncommon. Most examples are not simple alternatives of trees with crops, but involve an element of spatial intercropping. In an agrosylvopastoral system from Ecuador, two years of food crops are followed by eight years of a fallow consisting of *Inga edulis* interplanted with banana and a forage legume, the last being grazed by pigs. The litter from *Inga* is assumed to improve soil fertility (Bishop, 1982). Early-stage data from Peru show that biomass production from *Inga* overtakes that of herbaceous fallows and equals or exceeds natural forest (Szott et al., 1987b).

In the *Acacia senegal* system of Sudan, trees are interplanted with food crops, and crop production continues for four years. This is followed by some 16 years during which the trees are tapped for gum arabic and soil fertility builds up (M.M. Ballal, personal communication).

Short, sub-annual tree fallows are also possible. Tree fallows amid rice were a traditional practice in north Vietnam (Tran Van Nao, 1983). In north-west India, *Sesbania cannabina*, grown under irrigation for 65 days between wheat and rice crops, added 7300 kg DM/ha and 165 kg N/ha (Bhardwaj and Dev, 1985).

A question of fundamental importance for agroforestry design is the relative efficiency in soil improvement of a rotational tree fallow and a spatial, concurrent arrangement of trees. Most observed rotational tree fallows occupy well over 50% of time in the tree-crop cycle, a ratio that would be economically unacceptable as a ratio of areas in space. The apparent success of hedgerow intercropping, in which the tree cover is generally below 35%, suggests a greater efficiency for spatial systems. Mechanisms leading to greater efficiency of nutrient recycling under spatial systems would seem to be the cause, but what these are is not known; the answer could lie in the permanence of the tree rooting system.

There is no direct information on this basic question. Research stations should set up controlled trials, in which the effects on soils of the same tree species, management and tree:crop ratio are compared. This is most simply done by planting a rotational fallow adjacent to hedgerow intercropping trials.

Rather than simply alternate trees with crops, the most valuable systems are likely to be those that combine intercropping with rotation. Possibilities of this kind are discussed by Prinz (1986).

Taungya. In the taungya practice, food crops are either grown in rotation with commercial timber trees, or interplanted during the first few years of tree establishment. No-one supposes that this is very desirable as regards soil fertility. Many forestry trees do not leave the soil in good condition after felling, and food crop yields are fairly low. Conversely, it is suspected that annual crops may compete for nutrients with the newly planted trees. In Kenya, under the sequence montane forest, food crops, plantation forestry (*Vitex, Cupressus, Pinus patula, Grevillea*), soil carbon and phosphorus were substantially lower under the plantation than the forest; it was assumed that the fall in fertility occurred during the cropping period, but no samples were taken at the period needed to test this (Robinson, 1967). Studies of soil changes under plantation forestry are relevant (Lundgren, 1978; Adlard and Johnson, 1983).

The taungya practice appears to be neutral to adverse from a soils viewpoint, becoming seriously undesirable only if substantial erosion is allowed to occur.

Spatial-mixed practices

Trees on cropland. Many kinds of trees are grown on cropland for productive purposes, without having any clear adverse affects on adjacent crops. A small number of species are planted or, more often, preserved in part for their beneficial effect on soils and crop yields, known by farmers and in some cases demonstrated by scientists. Examples and evidence for *Acacia albida, A. senegal, Paulownia* spp., and *Prosopis cineraria* have been given above. These are spatial-open systems (as compared with the spatial-dense systems such as home gardens). Where such effects occur, it seems logical to augment them by increasing the tree density to something approaching a full canopy, or until light reduction counteracts the improvement in crop growth.

Multistorey tree gardens. Home gardens epitomize the qualities claimed for agroforestry systems. They are highly productive, fully sustainable and very practicable. They are a feature mainly of the humid to moist subhumid tropics (Fernandes and Nair, 1986).

The maintenance of soil fertility is achieved by a combination of inputs, particularly household waste, and a high level of recycling of organic matter and nutrients. The many species present lead to a large litter fall with a range of properties. A large biomass production by bamboos is a common feature. The multi-level root system may be a factor contributing to efficient nutrient recycling.

These features are so obvious that no-one has measured them. A nutrient-cycling study of a home garden would be of interest in showing the magnitudes of nutrient flows and the degree of recycling. With less effort, a comparison of soil properties within home gardens and on adjacent agricultural land could be made. Can home gardens match the degree of closure in nutrient cycling and the physical and chemical soil conditions found under natural vegetation?

Multistorey tree gardens covering wider areas than home gardens are also found. Because of the less intensive inputs, their effects on soils are likely to be less strongly favourable than those of home gardens, comparable with those of plantation crop combinations.

Plantation crop combinations. Combinations of coffee or cacao with *Erythrina, Inga*, and *Cordia* form a widespread agroforestry system in Central America. It is also one of the only two agroforestry practices on which a substantial quantity of soils research exists. These are listed in Table 29.

The main trees included are *Erythrina poeppigiana* and other *Erythrina* species, *Inga jinicuil* and *I. leptoloba*, sometimes with bananas or fruit

Table 29. *Soil studies of plantation-crop combinations.*

Reference	Country	System	Soil aspects
Jimenez & Martinez (1979)	Mexico	Coffee+*Inga*, fruit trees	Biomass
Aranguren et al. (1982)	Venezuela	Coffee+*Erythrina, Inga*	N cycle
		Cacao+*Erythrina, Inga*	N cycle
Bornemizsa (1982)	Colombia	Coffee+*Inga*	Biomass, N cycle
Roskoski (1982)	Mexico	Coffee+*Inga*	N fixation
Roskoski & van Kessel (1982)	Mexico	Coffee+*Inga*	N fixation
Glover & Beer (1986)	Costa Rica	Coffee+*Erythrina*	Biomass, nutrient cycles
		Coffee+*Erythrina*, Cordia	Biomass, nutrient cycles
Russo & Budowski (1986)	Costa Rica	Coffee+*Erythrina*	Biomass, nutrient cycles
Alpizar et al. (1986, 1988)	Costa Rica	Cacao+*Erythrina* Cacao+*Cordia*	Biomass, organic matter, nutrient cycles
Loué (n.d.)	Ivory Coast	Coffee+*Albizia gummifera*	Leaf and soil nutrient differences
Beer (1987)	Latin America	Various	Summary, effects of trees

trees, and *Cordia alliodora*. The plantations may be fertilized. *Erythrina* is usually pruned regularly. *Cordia* is allowed to grow into a mature tree before harvesting for timber. These are usually called 'shade trees', but it is clear that their functions include soil amelioration (Beer, 1987). This role is recognized by farmers. The salient results of these studies are:

1. Large quantities of biomass are returned to the soil, as litter and prunings, both from the coffee/cacao and trees. Values given as kg DM/ha/yr are as follows:

Mexico	Coffee alone	6000	Jimenez & Martinez (1979)
	Coffee, *Inga*	8400–9500	
	Coffee, *Inga, Musa*	10 200	
Colombia	Shade trees	4600–13 100	Bornemisza (1982)
Costa Rica	Coffee, trees trees providing half	16 000–17 000	Glover & Beer (1986)
Costa Rica	*Erythrina*		Russo & Budowski (1986)
	2 pollardings per year	11 800	
	1 pollarding per year	18 500	
	including litter	22 700	
Costa Rica	Cacao	7000	Alpizar et al. (1986, 1988)
	Cordia	10 400	
	Cacao, *Cordia*	17 400	
Costa Rica	Cacao	7000	Alpizar et al. (1986, 1988)
	Erythrina	9400	
	Cacao, *Erythrina*	16 400	

2. There is substantial nitrogen fixation by *Erythrina* and *Inga jinicuil*, giving values in kg N/ha/yr fixed of:

Colombia	*Inga jinicuil*	40	Bornemisza (1982)
Mexico	*Inga jinicuil*	47	Roskoski (1982)
Mexico	*Inga jinicuil*	35	Roskoski & van Kessel (1985)

3. There is a large return of nutrients to the soil in litter and prunings, especially but not only nitrogen, giving values in kg/ha/yr of:

		N	P	K	Ca	
Venezuela	Coffee leaf	28				Aranguren et al. (1982)
	Tree leaf	78				
	Twigs, flowers, fruit	66				
	Coffee + trees	172				

		N	P	K	Ca	
Costa Rica (fertilized)	Coffee	148	8	88	87	Glover & Beer (1986)
	Trees	183	14	74	241	
	Coffee + trees	331	22	162	328	
Costa Rica	*Erythrina poeppigiana*	330	32	156	319	Russo & Budowski (1986)
Costa Rica (fertilized)	Cacao	43	8	30		Alpizar et al. (1986, 1988)
	Cordia	71	6	35		
	Cacao, *Cordia*	115	14	65	125	
Costa Rica	Cacao	53	3	27		Alpizar et al. (1986, 1988)
	Erythrina	122	7	27		
	Cacao + *Erythrina*	175	9	54	163	

These nutrient returns are sometimes as high as rates of fertilizer application.

The Central American studies do not include monitoring of soil changes over time. It is, however, clearly implied that the soil is maintained in a stable and fertile condition. Aranguren et al. (1982) give values, for depths of 0–20 and 20–30 cm respectively, of 5.3 and 4.1% carbon, which are similar to soils under natural vegetation for this climate.

For six sites in Ivory Coast, Loué (n.d.) compared nutrient contents of coffee leaves and soils for plantations with and without *Albizia gummifera* shade trees. For coffee leaves, the average enrichment for shaded sites was 23% for nitrogen and 16% for phosphorus, whilst potassium showed wide variations. For soils, shaded plantations had slightly higher (non-significant) nitrogen and phosphorus, but were 46% lower in potassium, suggesting that *Albizia* draws potassium from the soil.

For the Central American plantation crop combinations, the following effects of 'shade' trees have been identified (Beer, 1987):

- improvement of drainage and aeration by roots
- provision of mulch
- increase in soil organic matter
- reduction of erosion
- reduction of the rate of soil organic matter decomposition
- recycling of nutrients that are not accessible to crops
- nitrogen fixation
- less need to use chemical herbicides which inhibit beneficial soil organisms.

Spatial zoned practices

Hedgerow intercropping (alley cropping, barrier hedges). In hedgerow intercropping, rows of trees or shrubs (the hedgerows) are intercropped with herbaceous crops in the spaces between (the alleys). It is commonly called alley cropping, although this name is less appropriate in that it refers to only one of the two components. Where established on slopes, with the primary objective of erosion control, it may be called barrier hedges, but no clear difference exists between barrier hedges and hedgerow intercropping on slopes. Hedgerow intercropping has aroused more current interest among scientists than any other agroforestry system. Well over half of all diagnosis and design studies have suggested it as an intervention to help solve land-use problems. Among reasons, the potential for maintenance of soil fertility is usually cited.

It is also one of two agroforestry practices on which substantial soils research has been done. Table 30 gives some published studies. Many more will appear as a result of trials recently started or planned. The salient results from these studies are:

1. A large biomass production can be obtained from hedgerows, typically 2000–5000 kg DM/ha/yr in moist subhumid climates, up to 10 000 in humid climates. These values are per hectare of total land in the system.
2. Large amounts of nitrogen can be fixed by hedgerows, e.g. 75 to 120 kg N/ha in six months by *Leucaena* (Mulongoy, 1986).
3. Substantial quantities of nutrients are contained in hedgerow prunings, and can thus be added to the soil if the latter are not harvested, giving values in kg/ha/yr of:

		N	P	K	
Nigeria	*Leucaena leucocephala*	105	4		Agboola (1982)
	Gliricidia sepium	84	4		
	Tephrosia candida	118	7		
	Cajanus cajan	151	9		
Nigeria	*Leucaena leucocephala*	200			Kang & Bahiru Duguma(1985)
	Gliricidia sepium	140			
	Acioa barteri	29			
	Alchornea cordifolia	84			
Nigeria	*Gliricidia sepium*	238	14	152	Yamoah et al. (1986a)
	Flemingia congesta	78	8	57	
	Cassia siamea	186	20	100	
Sri Lanka	*Leucaena leucocephala*	105	5	37	Weerakoon & Gunasekera (1985)
Kenya	*Leucaena leucocephala*	196			Bashir Jama et al. (1986)

It is noteworthy that the non-nitrogen-fixing species, *Acioa* and *Alchornea* nevertheless contain substantial nitrogen, as does a species that is probably non-fixing, *Cassia siamea*. Up to 30% of the nitrogen in prunings reaches the crop, the rest being lost by leaching and gaseous losses (Mulongoy, 1986). Thus the likely contribution to crop nitrogen uptake is about 30–80 kg N/ha/yr; using a common rule of thumb of multiplying by 10–15, this factor alone could raise cereal yields by 300–1200 kg/ha.

4. Residues from prunings of most species used decompose rapidly, with corresponding release of nutrients. There is a corresponding rapid evolution of mineral nitrogen. *Leucaena* has particularly rapid decomposition, releasing 50% of nutrients in the first 25 days.
5. In many studies, both at Ibadan and elsewhere, there is at least one combination of hedgerow species and spacing in which crop yields are higher than on control plots without hedgerows. The Ibadan trials have consistently achieved this, and it is the case for at least one combination at most sites in a network of seven in different environments in Kenya (EDI, 1987; Amare Getahun, personal communication). This is despite the fact that crop rows close to the hedgerow usually (but not always) show a fall-off in yields.

Table 30. *Soil studies of hedgerow intercropping.*
A. At IITA, Ibadan, Nigeria.

Reference	Hedgerow species	Soil aspects
Kang et al. (1981, 1985)	*Leucaena leucocephala*	Soil changes, crop yields
Agboola (1982)	*Leucaena leucocephala, Gliricidia sepium, Tephrosia candida, Cajanus cajan*	Biomass, N and P in prunings
Kang & Bahiru Duguma (1985)	*Leucaena leucocephala, Gliricidia sepium, Acioa barteri, Alchornea cordifolia*	N in prunings
Kang et al. (1985)	*Leucaena leucocephala*	Soil changes, crop yields
Mulongoy (1986)	*Leucaena leucocephala*	N fixation, N in prunings, litter decomposition
Sumberg (1986)	*Gliricidia sepium*	Biomass
Wilson et al. (1986)	*Leucaena leucocephala, Gliricidia sepium, Acioa barterii, Alchornea cordifolia*	Nutrients in prunings, crop yields, litter decomposition
Yamoah et al. (1986a)	*Gliricidia sepium, Cassia siamea, Flemingia congesta*	Litter decomposition

Table 30 (cont)

Reference	Hedgerow species	Soil aspects
Yamoah et al. (1986b)	*Gliricidia sepium, Cassia siamea, Flemingia congesta*	Biomass, N, P, K in prunings, crop yields, roots
Yamoah et al. (1986c)	*Gliricidia sepium, Cassia siamea Flemingia congesta*	Soil changes
Bahiru Duguma et al. (1988)	*Leucaena leucocephala, Gliricidia sepium, Sesbania grandiflora*	Pruning regime effects
Sanginga et al. (1987)	*Leucaena leucocephala*	N fixation

B. At other sites.

Reference	Country	Hedgerow species	Soil aspects
de la Rosa (n.d.)	Philippines	*Leucaena leucocephala*	Crop yields
Weerakoon (1983)	Sri Lanka	*Leucaena leucocephala, Gliricidia maculata*	Biomass, crop yields
Weerakoon & Gunasekera (1985)	Sri Lanka	*Leucaena leucocephala*	Biomass, nutrients in prunings, crop yields, (rice)
Handawela (1986)	Sri Lanka	*Gliricidia maculata*	Soil properties, crop yields
Bashir Jama et al. (1986)	Kenya	*Leucaena leucocephala*	Biomass, nutrients in prunings, crop yields, soil changes (early stage)
Szott et al. (1987a)	Peru	*Inga edulis* *Erythrina* spp. *Cajanus cajan*	Biomass, soil properties (early (stage)
EDI (1987)	Kenya	Many species	Biomass, crop yield

By contrast, many trials show a decrease in crop yield per unit of total area. This is sometimes compensated by the value (to the farmer or as cash) of the fodder and/or fuelwood produced.

Both increases and decreases in crop yield caused by hedgerows may be due to a variety of factors, microclimatic as well as soil, and no studies have yet appeared which attempt to isolate these. This problem is very complex. A recent discussion, combining soils with other aspects, is given by Huxley (1986b).

15. Trees on cropland: *Acacia albida*. Mangoche, Malawi.

16. Hedgerow intercropping: *Leucaena leucocephala* with intercropped herbaceous legumes in the alleys. Hyderabad, India.

17. Hedgerow intercropping: maize growth after seven years' intercropping with *Gliricidia sepium*. Maha Illuppallama, Sri Lanka.

One study has indicated an apparent favourable effect on crop yields of hedgerow root systems, in that maize yields on plots with prunings removed were higher than on controls without hedgerows (Yamoah et al., 1982b).

There have been two studies in which soil changes have been monitored over time, both at Ibadan, Nigeria (moist subhumid bimodal climate). The first consisted of intercropping *Leucaena* with a maize-cowpea rotation (one crop of each per year) on a sandy soil under a moist subhumid climate (Kang et al., 1981, 1985). Soils on plots with prunings applied to the soil were compared with those on plots with hedgerows but with prunings removed (but no data were given for soil changes under crops only). Some results are given in Table 31A. Application of prunings led to higher organic matter, potassium, calcium and magnesium, and substantially improved

Table 31. *Soil changes under hedgerow intercropping (HI), Ibadan, Nigeria.*

A. Leucaena/maize, unfertilized plots, soil depth 0–15 cm (Kang et al., 1981, 1985).

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

B. Gliricidia sepium, Flemingia congesta and Cassia siamea with maize, soil depth 0–15 cm (Yamoah et al., 1986c).

	Soil changes over 2 years			
Treatment	C (%)	N (%)	Bray P1 (ppm)	Exchange K (me/100g)
Gliricidia				
without prunings	+0.13	-0.019	-33	-0.12
with prunings	+0.17	+0.001	-39	-0.11
Flemingia				
without prunings	-0.56	-0.088	+ 3	-0.29
with prunings	-0.23	+0.023	+22	-0.13
Cassia				
without prunings	+0.15	+0.023	+22	-0.31
with prunings	+0.70	+0.137	+29	-0.22
No hedgerows				
0 N	-0.17	+0.039	-21	-0.12
90 N	-0.14	+0.070	-16	-0.15

	Soil physical properties after 2 years		
Species	Bulk density (g/cm^3)	Mean aggregate diameter (mm)	Water content at saturation (%)
Gliricidia	1.26	0.77	39
Flemingia	1.25	0.57	36
Cassia	1.34	0.70	43
No hedgerows	1.53	0.46	35
S.E.	0.05	0.07	1.22

18. Pruned hedgerows of *Leucaena leucocephala* planted between alternate rows of maize. Zomba, Malawi.

19. Multistorey tree garden: coconuts, coffee and bananas on a steep slope. Mindanao, Philippines.

20. Home garden: high production combined with intensive recycling gives full sustainability. North of Hanoi, Vietnam.

the available water capacity. There were no differences in phosphorus. Soil organic matter was maintained over six years, compared with a decline where prunings were removed. These changes in organic matter have been modelled (p. 000). Although the data may not be fully comparable, potassium levels appear to be maintained over time, and calcium levels to rise.

The second Ibadan trial was on a ferric luvisol, 'infertile due to constant use' (Yamoah et al., 1986c). Hedgerows 4 m apart were established with *Gliricidia sepium, Flemingia congesta* and *Cassia siamea*, intercropped with two maize crops over two years. All plots received 60 kg/ha of both phosphorus and potassium; nitrogen treatments ranged from 0 to 90 kg/ha. For each hedgerow species, soil changes were compared with prunings removed and retained, plus a control with no hedgerows. The time period is very short to detect soil changes, and the statistical significance unknown, but there are some intriguing results (Table 31B). Organic matter decline in the control plot was reversed by *Cassia* and *Gliricidia*, even with prunings removed! The obvious suggestion is root residues. Nitrogen increased in the control, but at nearly twice the rate under *Cassia*, a supposed non-nitrogen-fixing species. Phosphorus improved under *Cassia* and *Flemingia*, but none of the hedgerows checked a decline in potassium. Soil physical properties were significantly better under all species than without hedgerows. The authors several times single out the favourable effects of 'the abundant and persistent mulch from the *Cassia*'.

Other data are fragmentary. In the subhumid zone of Sri Lanka, under an intercropping system with *Gliricidia maculata* at 5 m by 1 m, soil organic matter and nitrogen were better than on a control plot with maize only, and soil structure better (compressive strength lower) (Handawela, 1986). At Maha Illuppallama, Sri Lanka (moist subhumid climate), *Gliricidia sepium* intercropping plots are maintaining nitrogen levels but apparently, after a few years, encountering phosphorus deficiency (L. Weerakoon, personal communication). On the Kenya coast, early-stage results suggest an increase in carbon, phosphorus, potassium and calcium (Bashir Jama et al., 1987).

Reasons for supposing that hedgerow-intercropping systems can be designed which effectively control erosion, and thereby loss of nutrients in eroded soil, are discussed in Part II.

Hedgerow intercropping presents many problems, not least those associated with the long tree-crop interface, the highest in any kind of agroforestry other than spatial dense practices (Young, in press, b). If hedgerows are 1-m wide and cropped alleys 4-m, the interface is 4000 m per hectare. If soil, microclimatic or other interface effects are, on balance, favourable, then this is a good thing. If they are adverse in net effect, then hedgerow intercropping is unlikely to be successful. For the soil-based interactions alone, the above-ground effects are likely to be favourable to the crops, through nutrient additions from litter. Below-ground effects could be beneficial, through addition of organic matter and nutrients in root residues, or adverse, through hedgerow competition with crops for nutrients. Little is known about these effects.

Favourable effects on crop yields are most likely to occur in systems in which hedgerow prunings are applied to the soil. If they are harvested, effects will necessarily be much smaller, although roots may provide some benefits.

Most trials to date have been in humid to moist subhumid climates. However, performance in recently commenced trials in the dry subhumid zone, such as at ICRISAT (Hyderabad, India) and ICRAF (Machakos, Kenya), is not unfavourable.

Where hedgerow intercropping is established on slopes, it may be called a system of barrier hedges. In such cases there is a close integration of erosion control and fertility maintenance; erosion control is achieved in part by the litter cover of prunings, which contribute also to fertility.

HEDGEROW INTERCROPPING AND SOIL FERTILITY

Systems of hedgerow intercropping appear to have the capacity to maintain soil fertility, with low to moderate inputs, where the tree component occupies only 15–25% of the land.

This contrasts with systems of rotational fallow, in which the tree component normally occupies more than 50% of the rotation.

If this comparison is confirmed, it suggests that hedgerow intercropping is more efficient in its use of land and offers an alternative to shifting cultivation.

The processes by which this effect is achieved are not fully understood. Research into these processes will help support the design of sustainable systems for different conditions of climate, soil and slope.

Despite the fragmentary nature of the data, the hypothesis that hedgerow-intercropping systems can be designed to maintain soil fertility as well as being productive remains a distinct possibility. If proven, these systems could make a very large contribution to sustainable agriculture in the tropics, both on sloping lands and on soils with low or declining fertility.

Boundary planting. Because of the relatively short tree-crop interface, effects on soils are likely to be small, and could be positive, neutral or negative. This is the kind of spatial arrangement in which to plant trees which are wanted for production but may be adverse to soil conditions.

Trees on erosion-control structures. The spatial arrangements and functions of trees and shrubs for control of soil erosion have been discussed in Part II of this review. There are many opportunities for combining erosion control, which in itself is a means of maintaining fertility, with the other beneficial effects of trees.

For trees planted on grass barrier strips, bunds and terraces, the contribution to soils from tree litter is likely to be small but positive. *Grevillea robusta, Cassia siamea* and *Leucaena* are commonly employed in this way.

Windbreaks and shelterbelts. Whilst intended primarily to control wind erosion, there is an apparent potential to make use of the soil fertility effects of trees in this practice—the spreading of leaf litter on crops being achieved by the wind! Modern practice is to design windbreaks of several tree and shrub species with differing shapes, which gives opportunity deliberately to include some of the known soil-improving species that occur in semi-arid areas, such as *Acacia albida*, other acacia species, *Prosopis cineraria* and *Azadirachta indica*. It appears possible, through imaginative design of windbreaks, to achieve erosion control, microclimatic amelioration and improved soil fertility, a combination of high potential value to the semi-arid zone.

Biomass transfer. This refers to the practice, found for example in Nepal, of cutting tree foliage from natural forest and carrying it onto cropland. Doubtless it improves yields, or farmers would not undertake the enormous labour involved. If associated with cutting for fuelwood, there is likely to be degradation of forests.

Sylvopastoral practices

Trees on rangelands or pastures. Trees and shrubs contribute to sylvopastoral systems by direct provision of leaf fodder and through improvement of pasture growth beneath them. The effect on pastures can arise from many causes, including microclimatic amelioration and the effects of animals (domestic or wild) and birds, but it certainly includes an element of soil improvement.

Those trees which benefit crop yields, such as *Acacia albida* and *Prosopis cineraria*, have an equal, or probably greater, effect on pastures. Acacias in general appear to improve pastures, at least partly through nitrogen fixation. Evidence is provided by tree-soil transects under natural vegetation (p. 93). Relevant in this respect is the finding that, within certain rainfall limits, the productivity of Sahelian pastures is limited not by water, but by the availability of nitrogen and phosphorus (Penning de Vries and Krul, 1980).

The *dehesa* system of Spain and adjacent Mediterranean countries demonstrates complex interactions between trees, pastures, livestock and soils. Oaks (*Quercus rotundifolia* and other *Quercus* spp.) grow on rangelands, which are grazed by cattle, sheep, goats and pigs. There may be recurrent cereal cropping. Under oak canopies, both soil conditions and pasture growth are substantially better. Thus in Sevilla, Spain, soil organic matter, nitrogen, phosphorus and potassium were found to be about twice as high under trees than in adjacent pasture, nitrogen-mineralization higher, and calcium and magnesium 1.5 times as high (Joffre et al., 1988).

Such improvements in soils and pasture growth can be promoted through management only if there is opportunity to promote cover by selected tree species, either by planting or protection of natural seedlings against browsing of the growing shoot. Agroforestry in rangelands is unlikely to be successful unless applied in conjunction with basic principles of pasture management, such as control of livestock numbers and rotational grazing. Given socio-economic circumstances which allow such management, there is a clear potential for soil improvement through the use of trees.

Other sylvopastoral practices. Combinations of plantation crops with pastures, such as grazing under coconuts, are adopted primarily for purposes other than soil improvement, although a grass-legume ground cover can contribute to growth of the plantation tree through nitrogen fixation and recycling. The practices of live fences and fodder banks have no direct implications for soil fertility.

Practices with the tree component predominant

Woodlots with multipurpose management. This practice refers to planted forests which are managed with the intention of multiple production, for example forest grazing or tree fodder, possibly at the cost of not maximizing wood production. There is often an element of conservation in such areas, and the planting of trees which are desirable from the point of view of soil fertility should be among the aspects taken into account in design.

Reclamation forestry leading to multiple use. Like multipurpose windbreaks, this is another area of which the potential has been little explored. Reclamation forestry is a known and successful means of restoring areas of degraded soils, through the effects of the forest litter cover in checking erosion and building up soil organic matter and nutrient status.

There are opportunities to combine such reclamation with productive agroforestry, by a two-stage approach. In Stage I, reclamation, a complete forest cover is established and protected. In Stage II, controlled production with protection, management is modified in such a way as to maintain a sufficient degree of conservation but permit controlled production. The latter might include any combination of fuelwood, grazing, cut-and-carry grass or tree fodder, or even limited cultivation. Management measures to achieve this could consist of either a thinning of the tree cover or a selective clearance along contour-aligned strips. Such systems might be designed for reclamation of eroded soils, saline soils or sand dunes. Some of the trees planted for the reclamation stage could be selected with a view to their functions in the productive stage, for example nitrogen-fixing species which improved pasture growth. Examples have been noted above (p. 74).

Practices with special components

In *aquaforestry*, the effects on soils are highly specialized. A known system is the planting of trees, for example *Sesbania* spp., around borders of fishponds, with reported benefits to nutrient content of the water and therefore nutrition of fish. In combinations of mangroves with fishing there could be some comparable effects. The practice of *entomoforestry* (trees with insects, e.g. bees, silkworms, butterflies) has no direct implications for soils.

Summary: effects of agroforestry practices on soil fertility

A tentative grouping of agroforestry practices according to their effects on soil fertility is given in Table 32. There is clear scientific evidence for beneficial effects upon soils of some systems of *trees on cropland* and *plantation crop combinations*. Although lacking evidence of this kind, there is no doubt that *home gardens* maintain soil fertility. The labour input of farmers attests the effectiveness of *biomass transfer* as a method of fertilization.

Table 32. *Agroforestry practices in relation to soil fertility.*

- Practices with substantial positive effects on soil fertility
  - Improved tree fallow
  - Trees on cropland
  - Plantation crop combinations
  - Home gardens
  - Hedgerow intercropping
  - Trees on erosion-control structures
  - Windbreaks and shelterbelts
  - Biomass transfer
  - Trees on rangeland or pastures
  - Woodlots with multipurpose management
  - Reclamation forestry leading to multiple use
- Practices with smaller positive or neutral effects on soil fertility
  - Boundary planting
  - Plantation crops with pastures
- Practices with positive or negative effects on soil fertility
  - Shifting cultivation
- Practices with neutral or negative effects on soil fertility
  - Taungya

The limited available results suggest that, for a range of environments, it is possible to design systems of *hedgerow intercropping* which maintain soil fertility. Given that this is a new practice, further evidence, from nutrient-cycling studies and soil monitoring, is needed before this can be taken as proven.

For the practice of *trees on erosion-control structures*, large improvements to soil fertility arise from the reduction in losses of organic matter and nutrients attributed to erosion control; the trees have a supplementary effect through addition of litter. The same combination of a large fertility effect through wind-erosion control with potential for further improvement by tree litter applies to *windbreaks and shelterbelts*.

For *trees on rangeland or pastures*, there is clear evidence that some trees promote pasture growth beneath them and that this leads to, or is associated with, improved soil fertility. For this to occur, it must be associated with good pasture management.

The adaption of *woodlots* and *reclamation forestry* into agroforestry through management for multiple use carries with it the known beneficial effects of a forest cover, given appropriate tree species and good management.

Improved tree fallow could have benefits similar to or greater than natural fallow in shifting cultivation, but there is no experimental evidence.

Design, management and integration

> Labourer: 'And as we reaped, we used to sing.'
>
> Interviewer (eagerly): 'What songs did you sing?'
>
> Labourer: 'Songs don't matter. It were the singin'
> as counted.'
>
> Interview between an elderly English farm labourer and an enthusiastic young sociologist, concerning conditions around 1900.

As in all branches of agriculture and forestry, sound design and good management of an agroforestry system matter as much or more than the nature of the practice itself. The presence of trees does not necessarily control erosion nor maintain soil fertility; what matters is the way they are arranged and managed.

This applies with greatest force to practices that are new. It is certainly possible to conceive of a hedgerow-intercropping system which depresses crop production, fails to provide compensating products from the hedgerows, and neither controls soil erosion nor sustains fertility.

For any projected intervention of agroforestry into an existing land-use system, sound design is the first essential. The detailed techniques set out in the design stage of agroforestry diagnosis and design are intended for this purpose (Huxley and Wood, 1984; Raintree, 1987). Plant selection and system design in relation to local conditions of climate, soil and slope are important aspects. Specifically from a soil-fertility aspect, consideration must be given to which parts of the trees and crops are harvested and which returned to the soil, with production being balanced against soil amelioration. The second essential is that the system should be well managed, both from the basic aspect of maintenance and as regards flexible adaptation if failing performance indicates a need for change.

Agroforestry should not be treated in isolation, but as an element in land-use planning as a whole (Young, 1987c). At the farm level, examples of imaginative integration are the approaches called conservation farming in Sri Lanka and integrated land use in Malawi. In conservation farming in Sri Lanka, elements include mulching, minimum tillage, measures for pest control and agroforestry. In Malawi, trees are being introduced into farming systems gradually, with an initial emphasis on planting on marker ridges and other soil-conservation structures (Weerakoon, 1983; Wijewardene and Waidyanatha, 1984; Douglas, 1988).

Opportunities for including agroforestry along with other kinds of land use in integrated watershed management have been noted above (p. 75). Agroforestry can best achieve its potential, for soil conservation as for other purposes, where it is considered together with other major kinds of land use as an element in land-use planning.

Part IV. Agroforestry for Soil Conservation

Chapter 15

Modelling Soil Changes under Agroforestry

Objectives

It is clearly desirable to be able to predict how soil properties will change under specified agroforestry systems on a given site, and to be able to compare these with changes under other land-use systems, existing or proposed. If this could be done, then we should possess a valuable technique for evaluating proposed systems in terms of environmental impact, to be used alongside evaluation in economic and social terms.

There is a further need to estimate impact on soil in the design of agroforestry research. An agroforestry field trial takes five years or more to obtain useful results. Any possible aid that might help in its design is therefore welcome. Furthermore, no field trial can include all possible combinations of variables; once some field data have been obtained, it would be useful to be able to extend these to estimates of the impact on soils of designs that have not been tried, e.g. 'Suppose we had removed the crop residues and not retained them, would this system still be sustainable?'

Predictions require data, and nothing is more demanding of quantitative data than a computer model. It draws attention to any critical elements that are required in order to predict soil changes, and indicates how important it is that particular items of data are accurately obtained—in technical terms, the sensitivity of the model to particular variables. Modelling can therefore help field research scientists by indicating the data that are required if predictions of changes in soil fertility are to be made.

It should be emphasized that present knowledge of soil-plant processes is insufficient to be able to make such predictions with confidence. Besides the need for more experimental studies, we require a better understanding of some of the basic soil processes involved. By comparing model outputs for different data and assumptions, for example different values of the tree-proportionality factor in erosion or the humus-decomposition constant, we can see what advances in basic knowledge are needed if predictions are to be made with greater confidence.

It was with these needs in mind that a computer model was constructed, Soil Changes Under Agroforestry or SCUAF (Young and Muraya, in press,a,b). Its primary aim is to predict the effects upon the soil of specified agroforestry systems within given environmental conditions. In more detail, the objectives of the model are:

1. To make approximate predictions of the effects upon the soil of specified agroforestry systems within given environments.
2. To show what data are needed from agroforestry experimental work if such predictions are to be made.
3. To make use of these predictions as a tool in the design of agroforestry systems, either for selecting the most promising systems for initial trials or for improving systems for which some data on performance are available.
4. To indicate what advances in knowledge of plant/soil and soil processes are needed in order to improve the accuracy of such predictions.

OBJECTIVES OF THE SCUAF MODEL

- to predict the effects on soils of specified agroforestry systems in given environments
- to show what data are needed to make such predictions
- to use predictions in the design of systems for agroforestry research
- to indicate what advances in knowledge are needed in order to improve the accuracy of the predictions.

The SCUAF model is only described in outline here, with illustrations of some results. A detailed account of the basis and functioning of the model, which covers erosion, soil organic matter and nitrogen cycling, together with instructions for users, is given in Young and Muraya (in press, b). The model is available on diskette.

Basis of the model

Models exist for the prediction of soil erosion and for nutrient cycling, particularly nitrogen, under agricultural systems. Many of these are of considerable complexity. What is needed for the present purposes is a model which, first, is relatively simple, so that it can be used by people other than its designer and, second, is focussed on the specific situation in agroforestry.

The first need was met by constructing an input-output model, rather than one in which there is sophisticated modelling of processes. For the second, the essential basis is to have two plant components, tree and crop, which can be present either in a rotation or in a spatial system.

It is clearly desirable to include prediction of soil erosion, not only mass of soil lost but also its content of organic matter and nutrients. Next in importance is prediction of changes in soil organic matter, on the grounds of its multiple role in soil fertility, with respect to soil physical conditions and also because organic matter is itself a source of plant nutrients. Thirdly, the model should include cycling of the major nutrients, particularly nitrogen in view of the role of nitrogen-fixing trees, and phosphorus as the other nutrient which is most often a check to sustainability.

There is one important factor omitted from the present model, that of soil water. In dry savanna and semi-arid environments this is frequently the limiting factor to plant growth, and it is hoped to incorporate it in future development of the SCUAF model.

A year-by-year time basis was chosen, again in the interests of simplicity; this contrasts with modelling on short time periods, such as 10 days, in some process-simulation models. On sites with two growing seasons in a year, either the plant growth can be summed for both seasons or each season treated as if it were a 'year' in the model. Initial soil conditions and plant growth are input, and changes to the soil predicted for the first year; the effect of these changes on plant growth in the second year is then estimated, and used to predict further soil changes. This iterative cycle can be continued for as long as desired but with progressively decreasing confidence. For the prediction of sustainability, a 20-year period provides a good basis; the soundest application is to take experimental results for some three to five years and extrapolate these for a longer period.

A set of default values is included. In using published results as a means of validating the model, it was almost invariably found that some items of data were missing, most frequently information on roots. Best estimates had therefore to be supplied. In using the model for demonstration and training purposes, many items are not readily accessible. The model contains default values for all items, the values of which are set by the input of climatic zone, soil texture class and slope class. For example, if the user inputs a lowland humid climate and a medium-textured soil, the model sets values, such as initial soil carbon and rates of plant growth, that are typical of that environment. Estimates of the factors in the universal soil loss equation are set on the basis of slope, climate and soil. *All* default values are presented on the computer screen to users, who have the opportunity to change them—and should substitute observed data wherever possible.

A particular case is presented by soil processes. Much agroforestry research is conducted by scientists who are not soil specialists, and not in a position to estimate values such as litter-to-humus decomposition conversion ratios or humus decomposition constants. Best estimates of all such process constants have therefore been compiled from published specialized studies.

The model was calibrated by taking studies of natural ecosystems in different climates, assuming that the soil was in a steady state, and from published accounts of agriculture, forestry and the small number of soil studies of agroforestry systems.

Structure of the SCUAF model

The SCUAF model can be thought of as consisting of two compartments, a plant compartment and a soil compartment. The plant compartment treats what happens to the plant material—trees and crops—before it reaches the soil. It is essentially the same for both carbon and nutrient cycling. The soil compartment models what happens in the soil, taking as one of its inputs, outputs from the plant compartment. Modelling of erosion is a distinct subunit of the soil compartment.

The plant compartment

The plant compartment is included in the carbon model shown in Figures 16 and 17, the former in simplified form. In any agroforestry system there are two plant components, called TREE and CROP (where CROP can be pasture). The TREE is partitioned into four parts, LEAF (herbaceous matter), FRUIT (reproductive matter), WOOD and ROOT. The CROP will usually contain only LEAF, FRUIT and ROOT, but the possibility of including a WOOD component is included in order to cover cases such as coffee (CROP) beneath shade trees (TREE). The source of carbon for plant growth is the atmosphere, through the process of photosynthesis. The user is asked to input the initial rates of net primary production of each plant component, partitioned into its parts.

For the carbon cycle, the values for dry matter given as net primary production are converted to carbon, taken by default as 50%. For the nutrient cycles, estimates are required of the nutrient content of each plant part, as fresh leaves in the case of prunings but at the time of shedding in the case of natural litter.

The user next specifies the *agroforestry system*, as spatial or rotational. If spatial, the percentages of land under tree and crop components (which can add up to more than 100%) are entered. If rotational, the user is asked how many years are under crops and under trees. In some agroforestry systems, the tree component is allowed to grow for a number of years, after which it is cut in some way, e,g. coppiced, pollarded or felled; this is called a *cutyear*. Where there is annual pruning, the cutyear is entered as one.

Some of the plant parts will be removed from the system as harvest or, in some systems, browse or burning. CROP FRUIT, the main food harvest, will always be removed, whereas CROP LEAF, the crop residues, may or may not be harvested. There may be an additional harvest in the cutyear,

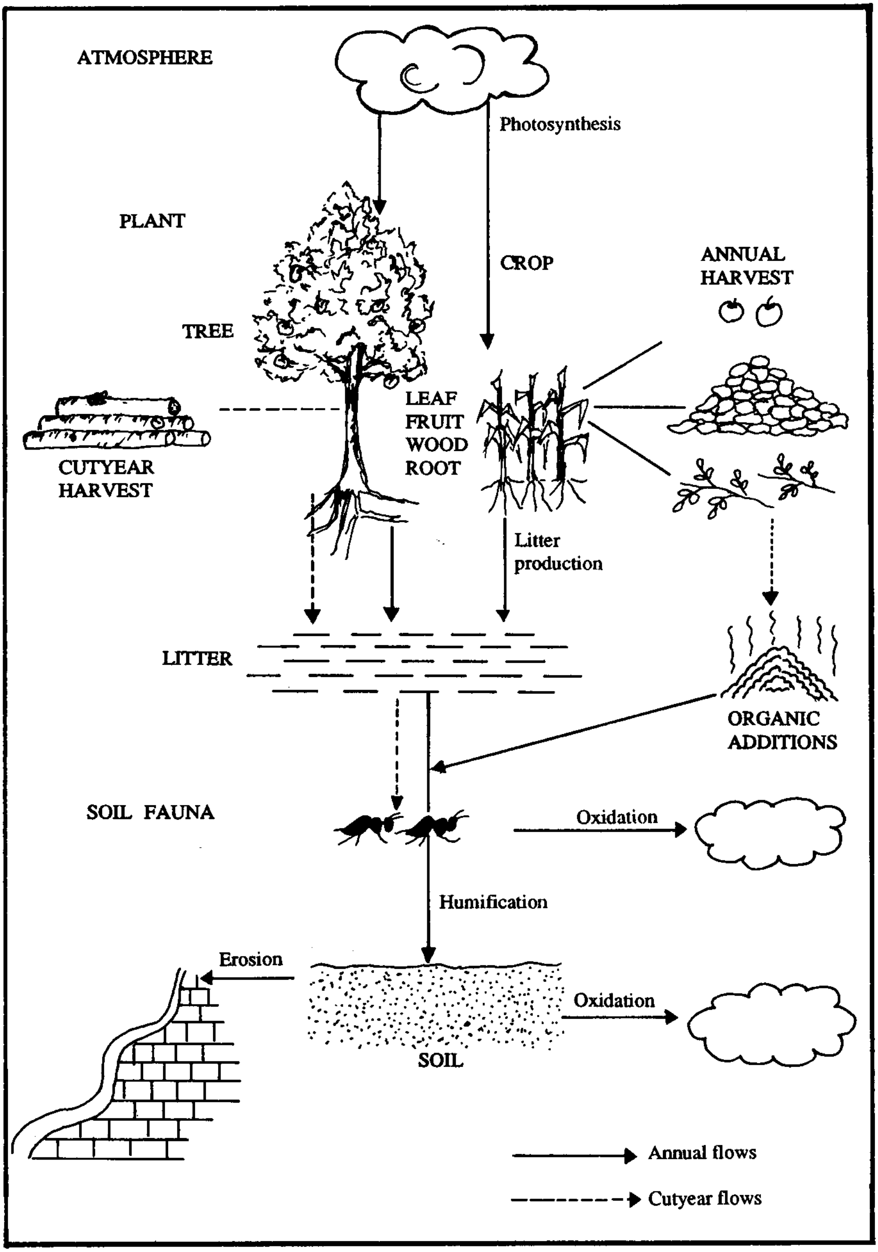


Figure 16. Outline of the SCUAF carbon cycle model, simplified.

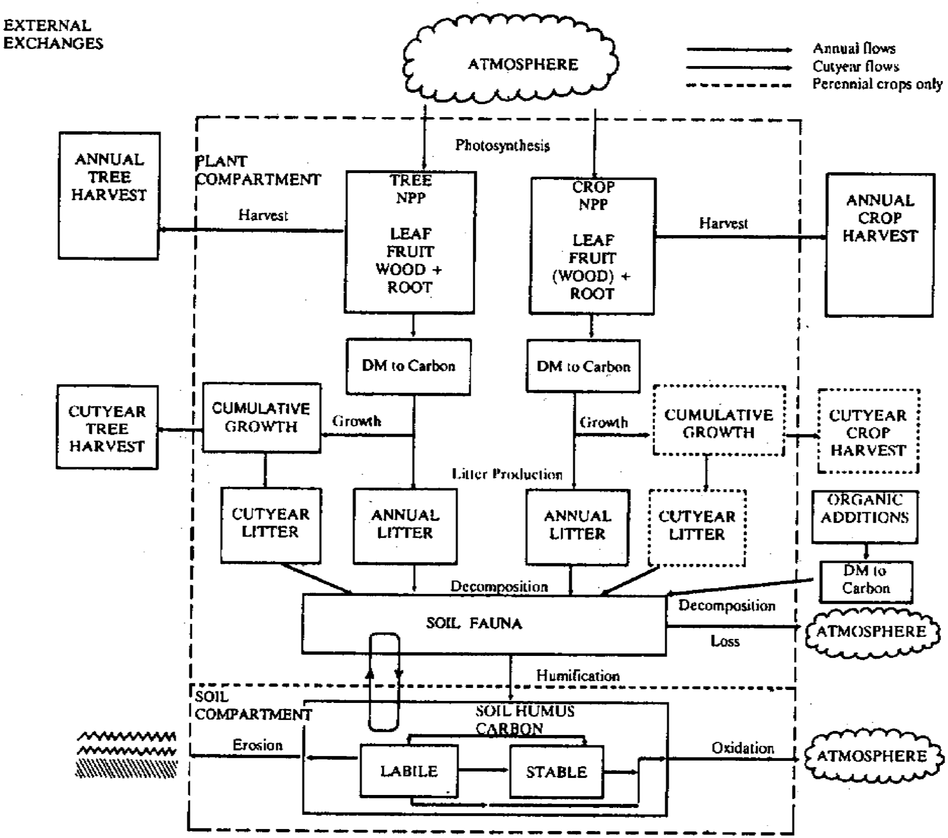


Figure 17. Structure of the SCUAF carbon model.

particularly of TREE WOOD, as timber or fuelwood. In some systems there are ORGANIC ADDITIONS originating outside the system, such as compost or manure. Some of the harvest may have been fed to livestock, and farmyard manure returned; this can be included in the model—but the transfer must be made by hand!

Out of these nine plant components (two plants, each with four parts, plus organic additions), what is not harvested or otherwise lost becomes LITTER, which includes prunings and root residues. The output of LITTER from the plant compartment, with its content of carbon and nutrients, becomes an input to the soil compartment.

Erosion

Soil erosion is calculated from the equation:

Erosion (kg/ha/yr) = R × K × S × C × 1000
where R = climate factor
K = soil erodibility factor
S = slope factor (LS in the USLE)
C = cover factor.

In each case, the factors may be obtained either by the simplified methods given in the FAO system (intended for use in estimating average erosion over large areas) or, where data permit, by the more sophisticated methods given in the USLE (intended for estimating erosion on individual farm fields).

When these factors have been entered, the model calculates values of erosion separately for the tree and crop components, and displays them. For rotational agroforestry systems, these values are used in the respective years under the tree or crop components. For spatial systems, the user enters the tree-proportionality factor. The model then displays the calculated rate of erosion for the system as a whole. The calculated values both for the tree and crop components alone and for a combined spatial system can be over-ridden by entering measured rates of erosion.

Having obtained erosion as kilogrammes of soil per hectare per year, losses of carbon and nutrients are calculated, together with reduction in soil profile depth. For carbon and nutrients, the proportions present in the original topsoil are multiplied by enrichment factors for eroded sediment (p. 45). For example, erosion of 5000 kg/ha/yr from a topsoil with 0.1% nitrogen and a nitrogen-enrichment factor of 4.0 would produce a loss of 5000 × 0.001 × 4.0 = 20 kg N/ha/yr. Change of profile depth is calculated from dry bulk density.

This gives erosion of soil, carbon and nutrients for the initial year. For subsequent years, climate and slope will remain the same but the soil and cover factors will be modified, with increase or decrease in soil organic matter and in plant growth. These are calculated in year-by-year iterative fashion.

Soil humus carbon

The annual balance of soil humus carbon, C, is given by:

$$C_{t+1} = C_t + \text{additions} - \text{oxidation} - \text{erosion}$$

where t and t+1 are successive years, additions are from humification of litter, oxidation is loss of CO_2 by soil fauna and erosion is loss of carbon in eroded soil.

Additions are calculated from the material in the various plant parts which become litter, multiplied by the litter-to-humus conversion losses for above-ground and root residues. This includes all plant carbon that is oxidized in less than one year, and is thus a large loss. The lack of information on its value for different circumstances is the greatest uncertainty in the carbon submodel.

Loss by oxidation is based on the decomposition constant (p. 108). The user may specify either one or two humus fractions, the latter called labile and stable, with stable humus having a considerably slower rate of decomposition. The equations employed for one- and two-fraction oxidation losses are given on pp. 108 and 111. The user can choose which depth of soil profile to include for carbon cycling. For the non-soil specialist, the working assumption for general agroforestry research proposed above is recommended, namely to select the topsoil only (15 or 20 cm), and to assume that most of the humus contained in it belongs to the labile fraction, i.e. to assume one humus fraction.

Soil fauna are included as an agent in processes, being responsible both for litter conversion loss and humus oxidation. As the carbon within their biomass is relatively small, however, it is not separately determined.

The carbon-cycling submodel is based essentially on the descriptive analysis made by Nye and Greenland (1960), adapted to permit two humus fractions. Thus modified, it is notably similar (although independently constructed) to the carbon section of the CENTURY model of Parton et al. (1987), where CENTURY's plant carbon, active soil carbon, slow soil carbon and passive soil carbon are SCUAF's litter, soil fauna, labile humus and stable humus respectively.

Nutrient cycling

The nutrient cycles in SCUAF consist of input-output modelling of the cycles shown in Figure 12, with the gains and losses from the soil as listed on p. 133. For each nutrient, there is a soil input consisting of the nutrients reaching the store of litter.

For the nitrogen cycles, the user states, when specifying the agroforestry system, what proportions of the tree and crop components are nitrogen fixing and how much nitrogen would be symbiotically fixed by a pure stand of the nitrogen-fixing components (see Table 22). Nitrogen fixing of the system as a whole is then calculated proportionally to time or space occupied. Loss of nitrogen by erosion is calculated as noted above. Fertilizer added is entered, and gains from atmospheric deposition and non-symbiotic fixation estimated.

The pool of available mineral nitrogen is calculated and partitioned between gaseous losses, fixation on clay minerals, leaching, erosion and plant uptake. The total nitrogen available to plants is the sum of uptake from the soil mineral pool plus that obtained directly by symbiotic fixation. It will be apparent that there are some large uncertainties (as in all other nitrogen-cycling models), notably the loss through leaching, data on which can only be obtained by lysimeter studies. Default values for climate and soil texture are included, obtained by review of publications.

The phosphorus cycle is similar, except that input from weathering of rock minerals is substituted for atmospheric fixation; losses by fixation onto clay minerals are relatively more important, with default values dependent on soil acidity. The difficulty in measuring or estimating nutrient inputs from rock weathering adds a further element of uncertainty.

There is an argument that if a process cannot be measured, or estimated with reasonable confidence, then it should not be employed in calculations. If this is accepted, then nutrient cycling cannot yet be modelled. The view taken in the SCUAF model is that it is better to set best estimates, however uncertain, as default values than to omit some processes altogether.

Feedback effects of soil changes on plant growth

The rates of tree and crop growth input to the model are those under initial soil conditions. As the soil properties change, the growth of plants will be affected. This is modelled by means of feedback factors, operating within the annual time cycle of modelling. There are feedback factors for soil carbon, nutrients and soil depth.

The basis for each feedback factor is that a change in a soil property, relative to its initial conditions, produces some proportional change in plant growth. For example, if the carbon feedback factor for trees is set at 0.5, a 1% relative fall in soil carbon (e.g. 10 000 to 9900 kg C/ha) produces an 0.5% reduction in the rate of tree growth. With all feedback factors set to 0.0, rates of plant growth remain constant. Thus:

$$\mathrm{NPP}_t = \mathrm{NPP}_0 \times (1 + (((C_t - C_0)/C_0) \times \mathrm{CFF}))$$

where NPP_0 and NPP_t are net primary production initially and in year t respectively, C_0 and C_t are soil carbon initially and in year t, and CFF is a carbon feedback factor.

Feedback factors are given separately for trees and crops, and for carbon, nitrogen, phosphorus and soil depth. For the nutrients, feedback is based not on the organic reserves but on those in available mineral form. Default values are set at 1.0 for crops and 0.5 for trees, but the user should adjust these. Data from fertilizer trials may be employed (adjusted for the proportion of fertilizer nutrients reaching the plant). This is another case of the preference for a highly uncertain estimate to none at all—which would be equivalent to assuming that plant growth is unaffected by soil!

In practice, the feedback for loss of soil profile depth is almost always found to be negligible compared with that for loss of organic matter and nutrients, showing the invalidity of early attempts to calculate effects of erosion on productivity in terms of soil depth.

The SCUAF menu

Figure 18 gives a user's view of the SCUAF menu. There are three submenus, for inputs, outputs and utilities. The first input is to select which cycles are to be included: carbon, nitrogen or phosphorus, singly or in combination; in every case, erosion is included. Documentation sets a title, file name and other identification data. The spatial or rotational details of the agroforestry system are set, together with additions (organic or fertilizer) and removals (harvest or other losses). The initial conditions cover soil, erosion (factors or rate) and plant growth (tree and crop, partitioned into parts). The parameters in soil processes and the soil-plant feedback factors are then entered.

Apart from screen displays or printouts of the documentation and data, outputs consist of changes, over any specified period of years, in erosion (and its causative factors), soil humus carbon (one or two fractions), nitrogen, phosphorus, plant biomass production as affected by soil, total soil-plant system biomass and carbon, and harvest. The changes estimated for plant biomass production (growth) refer only to the effects of soil changes, not to the many other influences which affect plant growth. Harvest is a selection from the plant growth values of those items indicated as harvest, e.g. crop fruit, crop leaf (fodder) and tree wood (fuelwood).

Output is initially in the form of tables. A link to a commercial software package permits automatic production as graphs. The utilities menu allows a set of data to be stored, and subsequently retrieved.

All inputs and outputs operate independently. The user can therefore input a set of conditions and obtain outputs, or return to the input menu and change one or more values and obtain further outputs with all other values unchanged. This allows rapid comparison of conditions, e.g. 'What would be the effect if we could find a tree with 10% faster growth, or reduced the proportion of land under trees?'

Comparison with agricultural land-use systems can be achieved by using identical input data, but specifying an 'agroforestry system' consisting of 0% tree and 100% crops. Reversing these proportions allows the model to be used for reclamation forestry.

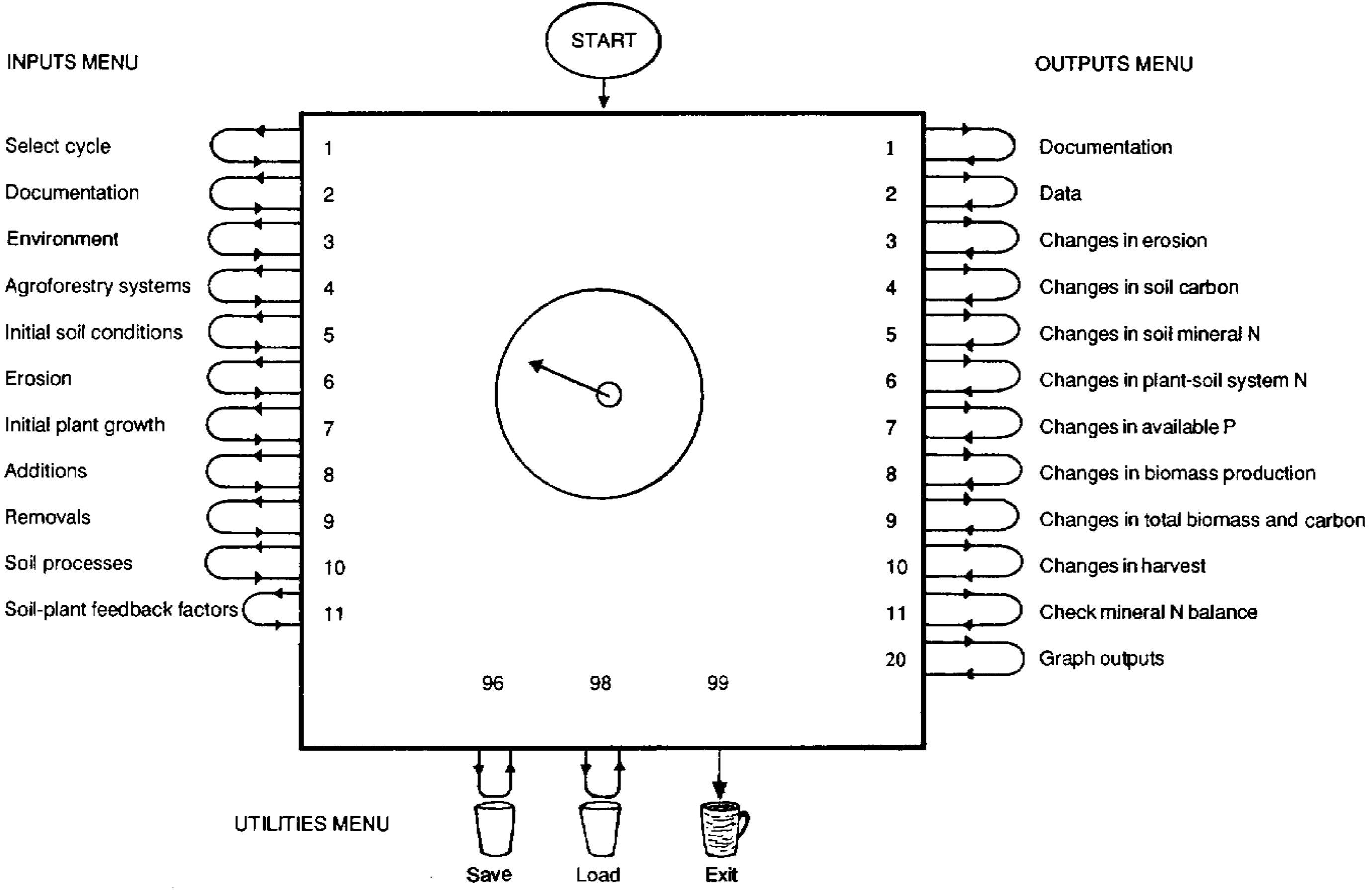


Figure 18. User's view of the SCUAF menu.

Examples

To illustrate the outputs from the SCUAF model, five examples are given, taken from rotational, spatial zoned and spatial mixed agroforestry systems. Other examples will be found in Young et al. (1987) and Cheatle et al. (1989).

Shifting cultivation is the only rotational agroforestry system for which there are data available (Figure 19). In a study some years ago in the Philippines, there was an average of three years' cultivation followed by 15 years' fallow (an R factor of 16.6%), under which it was implied that the system was sustainable (Kellman, 1969). The climate is lowland humid, and much land is steeply sloping. Erosion rates had been measured. The modelling of changes in soil carbon is given by the upper line in Figure 19. Decline during the period of cultivation is balanced by a rise during the forest fallow, with a 'jump' caused by inputs of root residues upon clearance. Also shown in the figure are the simulated effects of shortening the fallow to 11 and 7 years, leading to a soil-degrading system.

Figure 20 shows changes in erosion for a shifting cultivation system in which the fallow has been reduced to three years; data are simulated. The abruptness of the changes between cropping and fallow periods is not wholly realistic. Erosion increases for each year that the cropping period is continued; it is also greater at each successive return to the same point in the crop-fallow cycle, as a consequence of progressive soil degradation.

Figure 21 is based on a study of *Leucaena*-maize hedgerow intercropping at Ibadan, Nigeria, in which soil changes were measured after six years. The climate is lowland subhumid bimodal and the soil is sandy. The two upper lines are for plots with *Leucaena* prunings retained, the lower ones where these were removed, in both cases for unfertilized treatments. The circles are the observed soil carbon values. Using a decomposition constant of 4%, predicted soil carbon with the prunings retained rises to 18 000 kg/ha, above the observed value. A correct prediction is achieved by raising the decomposition constant to 6%. The considerable loss of carbon where prunings are removed (but crop residues retained) can only be simulated by a decomposition constant of 11%. These values are not unrealistic, however, since it is known that oxidation of humus is more rapid on sandy soils (Parton et al., 1987), and removal of prunings would leave the soil unprotected from the very high soil surface temperatures recorded at this site.

Figure 22 illustrates a spatial, mixed agroforestry system, the combination of cacao with *Cordia alliodora* (Alpizar et al., 1986, 1988). The climate is lowland humid (altitude 600 m, rainfall 2600 mm with no dry months) and the soil strongly acid, with quite high organic matter (topsoil carbon 2.5%). There is a fertilizer input of 120 kg N/ha/yr. Data for soil changes over time are not given, but it is implied that properties are stable, and explicitly stated to be so for nitrogen. In modelling, cacao is treated as the crop component. Using default values for soil processes, modelling shows a slow decline in organic carbon, which is restored if it is assumed that the *Cordia* are cut after 15 years and root residues enter the soil; in practice, there may be continuous, dispersed cutting. For nitrogen cycling, the data show an apparent gain to the soil (per hectare, per year) of 12 kg nitrogen and 13 kg phosphorus, and a loss of 50 kg potassium.

The last example illustrates the use of SCUAF in experimental design. In Figure 23, the initial data are taken from a study of maize monoculture on erosion plots in Ivory Coast, extrapolated by modelling to 10 years. The system is clearly degrading. After 10 years, this is replaced by a simulated agroforestry system, leaving all variables unchanged other than those affected by the introduction of a tree component. The major effect is a large reduction in erosion, which would probably take two to three years to achieve. With a proportion of trees typical of hedgerow intercropping, 20% or less, the system is still not fully sustainable. If the trees cover 40% of the land, there is a recovery in soil organic matter. This·leads to the question of whether an agroforestry system can be designed with this proportion of trees which meets other criteria of acceptability.

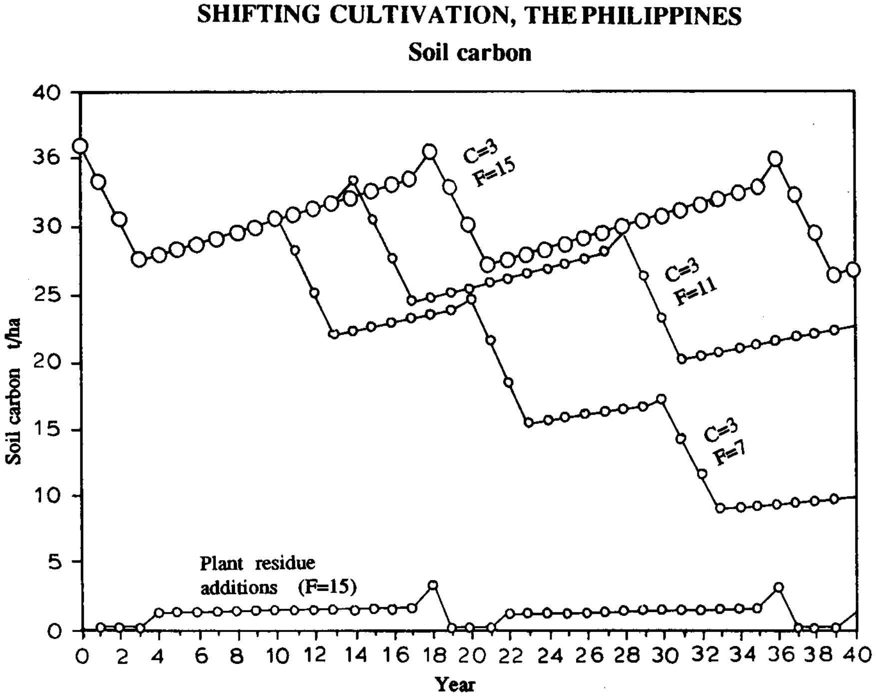


Figure 19. SCUAF outputs: changes in soil carbon under a rotational system, shifting cultivation, the Philippines. C = cultivation period in years, F = fallow period in years (data from Kellman, 1969).

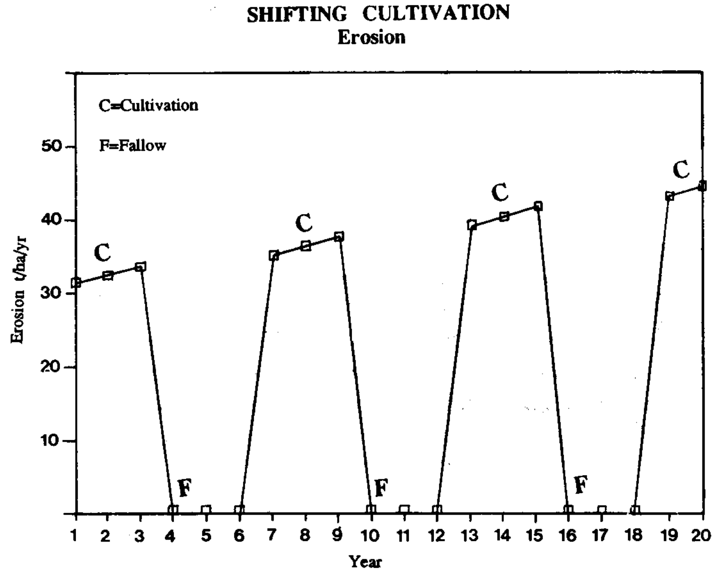


Figure 20. SCUAF outputs: changes in soil erosion under shifting cultivation with reduced fallow. Simulated data.

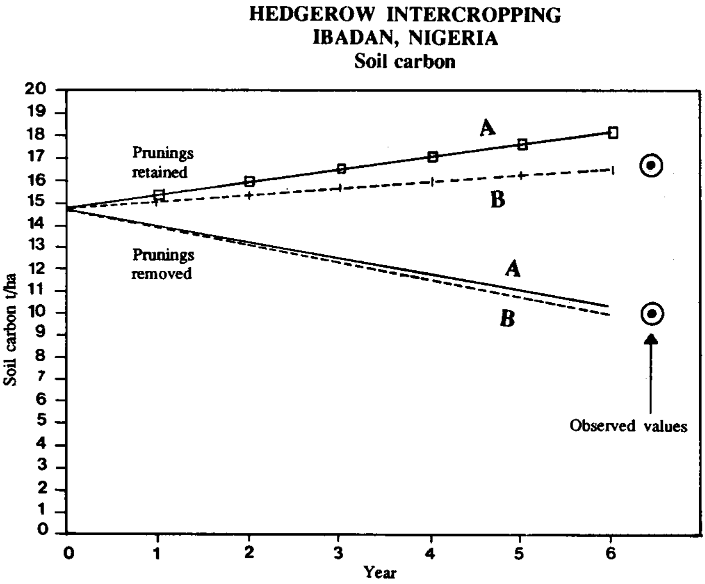


Figure 21. SCUAF outputs: changes in soil carbon under a spatial-zoned system, hedgerow intercropping, Ibadan, Nigeria. Lines marked A show predictions based on default values in the model, those marked B show modelling adjusted for experimental data (data from Kang et al., 1981, 1985).

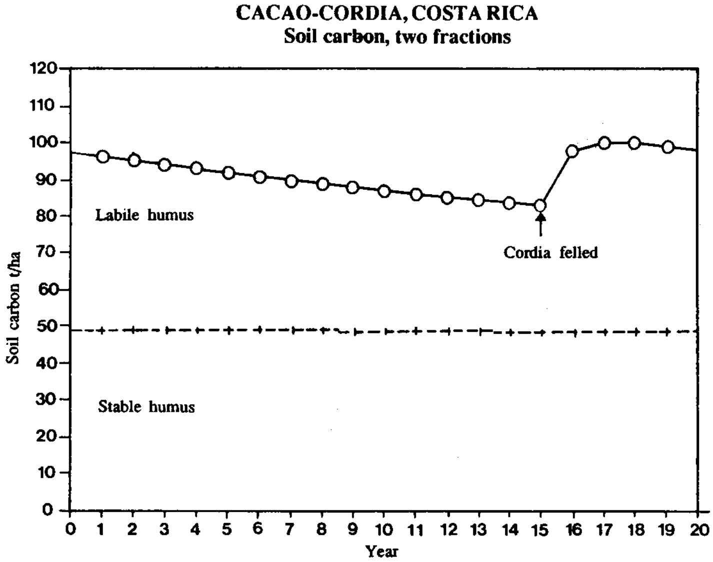


Figure 22. SCUAF outputs: changes in soil carbon and nitrogen under a spatial-mixed system, plantation crop combination of cacao with *Cordia alliodora*, Costa Rica (data from Alpizar et al., 1986, 1988). Carbon is modelled to 45 cm depth, assuming 50% is in stable form.

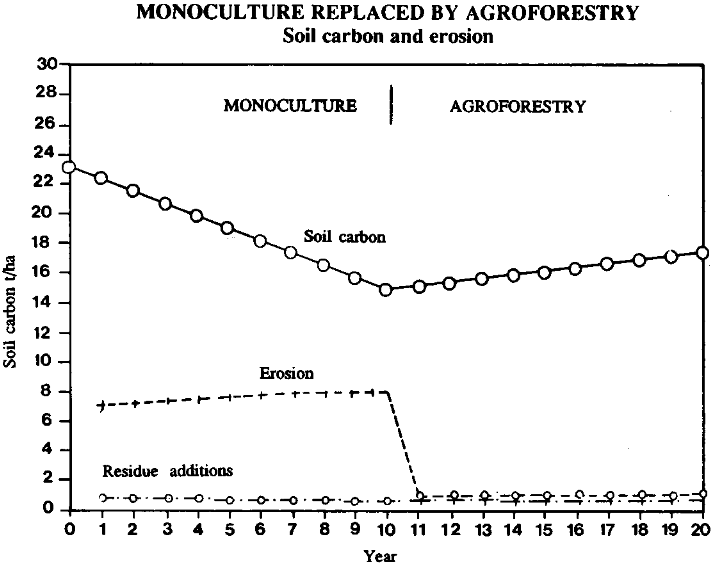


Figure 23. SCUAF outputs: changes in soil carbon and erosion, maize monoculture replaced by agroforestry (assumptions and data for monoculture from Lelong et al., 1984).

Chapter 16
Research

The need for research

Three conclusions from this review, taken in conjunction, indicate the need for research into the potential of agroforestry for soil conservation, treated in its broader sense as maintenance or improvement of soil fertility.

First, there exists in the tropics a widespread and increasing need for soil conservation. It is rare to find a study of existing agricultural systems which does not identify soil degradation, or fertility decline, as among the problems present, frequently one of the most serious. Where the land is sloping, erosion is one of the processes leading to decline in fertility; on steep slopes it is likely to be the dominant cause. Still more widely, the pressure of population upon land, combined with shortage of fertilizers and other inputs, has led to the situation formerly described as over-cropping and latterly as a failure to achieve sustainability. This is the situation in which, to meet the needs of the population, more is taken out of the soil than is put back into it, so causing degradation of a basic resource on which production depends.

Secondly, it has been shown that agroforestry appears to have the potential to control erosion, maintain soil fertility, and so lead towards sustainable land use. This applies not just to one system but to a range of agroforestry practices, each of which can be adapted into many different systems. Some at least of these practices are known to be acceptable to farmers, in that they are found as indigenous systems, whilst others have achieved a measure of acceptance in currently active extension projects. This range of design options means that there is scope to identify agroforestry systems suited to a wide range of environmental conditions and farmers' circumstances that are likely to contribute to soil fertility maintenance and sustainable land use.

Thirdly, it has been emphasized that much of the evidence for the previous conclusion is indirect. The capacity to control soil erosion is suggested by analysis of the causative factors and processes of erosion in relation to the characteristics of agroforestry systems. The potential to maintain soil fertility is inferred partly from the known beneficial effects of trees on soils. In the case of fertility maintenance, there are strong indications from indigenous agroforestry systems. But scientific evidence, in the narrow sense of controlled and replicated trials, is very scanty. At the time of writing, there is substantial experimental evidence only for hedgerow intercropping and dense, mixed plantation crop combinations, in both cases only from a few sites and under a narrow range of environments.

The conjunction of a large and growing need for soil conservation, a high apparent potential of agroforestry, and a scarcity of experimental evidence points clearly and strongly to the need for research.

THE NEED FOR RESEARCH

There is:

- a large and growing problem of soil degradation
- a high apparent potential of agroforestry to assist in the control of this
- a scarcity of experimental data to confirm this potential.

It is hard to imagine a combination of circumstances that so clearly indicates the need for research!

Levels of agroforestry research

At present, there is an explosion of activity in agroforestry research, the result of the rapid growth in awareness of its potential. Because of the urgency of the problems, brought about fundamentally by population growth and pressure upon natural resources, agroforestry is trying to achieve much in a short time. This calls for the structured planning of research.

Agroforestry systems are highly complex, involving the interactions of at least two plant components with each other and with climate and soil. As a consequence, scientific research in agroforestry can be thought of as falling into three levels: *what, why* and *how* (Huxley et al., 1989; Pinney and Young, in press) (Figure 24).

WHAT research is directed at questions of 'what happens?' It is intended to answer the immediate needs of farmers and other land users. Rural extension agents and farmers need advice on what tree species are appropriate to plant, in what number and arrangement, and with what management practices. Locally conducted trials of prototype systems, on-farm as well as on-station, are the level of research which directly precedes such advice.

WHY research seeks answers to questions of why the components of agroforestry systems perform in a certain way. Why does the crop on the upper side of a contour-planted hedge grow better than that on the lower side? Why is one tree species more competitive with an adjacent maize

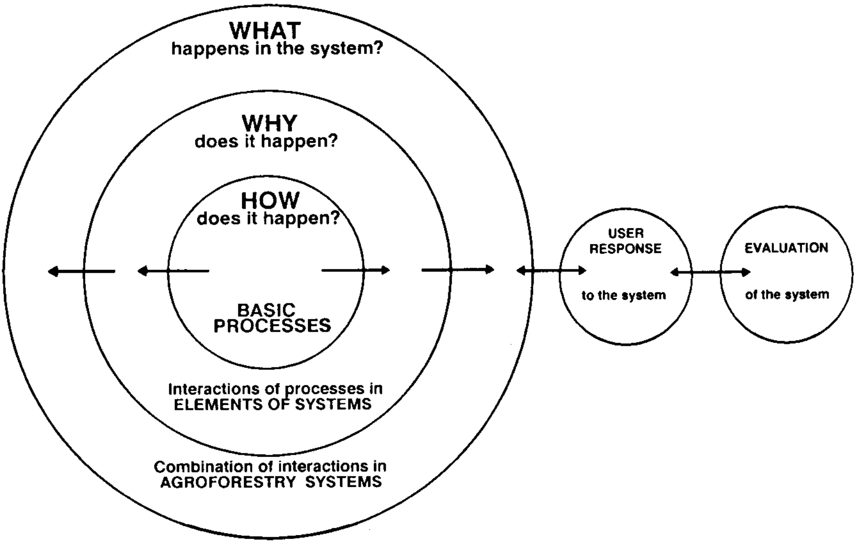


Figure 24. Levels of research in agroforestry (based on Pinney and Young, in press).

crop than another? This level of work is trying to determine cause-and-effect relationships operating on a specific site (soil, slope) and under each year's weather conditions. *Why* research is needed in order to design the prototype tested in *what* research.

HOW research is concerned with the fundamental processes operating within systems. How are mineralization rates affected by moisture? How does assimilate pass between roots of trees and crops? At this level we are looking at specific processes and effects, which operate as associations of effects in 'why' research. Some research at this level is not specific to agroforestry, but involves basic processes of, e.g., microclimatology, soil physics, soil biology and plant nutrition.

Beyond these levels of purely scientific research there are two more stages—user response and evaluation. User response tests the reaction to proposed agroforestry systems of farmers or other land users. Formerly thought of as a one-way procedure, designing systems on scientific grounds and then testing their acceptability, it is now common to include on-farm research and farmers' opinions and suggestions at an early stage of research planning. A structure for doing this is one feature of the diagnosis-and-design procedure.

Evaluation seeks to test the overall desirability of proposed systems, on environmental, economic and social grounds. It can be carried out at two stages, *ex ante*, analysing the apparent benefits and drawbacks of a system prior to its testing, using assumed data on performance; and *ex post*, analysis after the system has been in operation for some years with a view to improving it for the future.

The present expansion of interest in agroforestry has come at a time when there is also a focus on 'useful' research, directed at meeting the practical 'needs of farmers'. As a result, current agroforestry research is heavily concentrated on trials of potential systems (*what* research), at the expense of studies of basic processes. The statement, 'Research should be directed towards the practical needs of farmers' is true; but the reasoning, 'Therefore it should consist of field trials of practical management systems' is false.

The drawback with *what* or 'try-it-and-see' research can be seen from an example. Consider a single practice, that of hedgerow intercropping. On a given site it would certainly be possible to test four hedge species, three within-row plant spacings, four between-row spacings and three pruning heights; with three replicates this would give 432 plots—without considering alternative agricultural crops! Some saving is possible through partial replication and confounding, or the use of systematic designs, but the research effort needed remains considerable. Then, having found the optimum combination, all that is known is that it works on that soil, and in the weather conditions for the years of the trial. To carry out field trials without an understanding of basic processes is like research into chemistry before knowledge of the periodic table.

Studies at the *why* level, into the functioning of processes and their interaction within elements of systems, can lead to greater efficiency of research effort. If we understand how trees and crops share, and compete for, climatic and soil resources, we should be able to design agroforestry prototypes, systems that are likely to operate satisfactorily in a given set of conditions. It would be far-fetched to suppose that our knowledge of environmental interactions in agroforestry will ever reach the point when a precisely functioning system can be designed in this way, but the principle is applicable. Trials (*what* research) can then be conducted over small margins of variation. In this way, research at the *how* and *why* levels can lead to far greater efficiency in field trials of prototype systems.

Each level of research is appropriate for different types of institutions. *How* research calls for specialized knowledge and facilities, and is appropriate for universities, international institutes and specialized national or zonal organizations. *Why* research can be conducted at an international level, but should also form part of the work of the larger national agroforestry research organizations. Field trials of prototype systems are conducted at national level, preferably through a network of sites in different environments.

Objectives of research

Research into the soil-fertility aspects of agroforestry is a subject of much complexity and has many practical problems. It can be conceived in two parts: specialized soil studies, and soil observations in general agroforestry research. It is important that soil studies should not be confined to specialized institutions. Given the importance of maintenance of fertility as a fundamental feature of most agroforestry systems, some basic soil observations should form part of all general-purpose agroforestry field trials.

Specialized soil research

In specialized research, soil fertility is the primary objective. It is carried out by soil scientists at institutions possessing the necessary facilities. Some studies can be based on relatively straightforward methods of measurement, such as sampling and analysis, and require only good design and careful execution. Other aspects involve specialized techniques, for example isotope labelling (Young, in press, b).

The following problems require attention. In most cases, there is a need both for improvements in basic knowledge of the processes concerned, and for studies of their operation under trees and within agroforestry designs. 'Trees' refers both to individual trees and shrubs and to the tree component in agroforestry systems:

- Soil erosion: functioning of factors and processes under tree-crop mixtures; barrier and cover functions; processes within partly permeable hedgerow barriers
- Soil organic matter: formation, decomposition, cycling effects on fertility; role of herbaceous, woody and root residues in formation
- Nutrient cycling, especially efficiency of nutrient uptake and recycling by trees
- Tree biomass production, litter quality and decomposition
- Root and mycorrhizal systems of trees, and their effects
- Effects of trees on soil physical properties
- Nitrogen fixation by trees
- Effects of specific tree species on soil properties; what constitutes a good tree for soil fertility
- Studies of soil fertility under agroforestry systems, including organic matter, nutrient cycling, erosion and monitoring of soil change.

The major questions for soil-agroforestry research, expressed in the form of 10 specific hypotheses, are given in the box on p. 218. For only one subject, namely nitrogen fixation by trees, is the current research effort on a scale adequate to the needs. An appraisal of the current evidence for and against each hypothesis is given in Young (1989a).

TEN HYPOTHESES FOR SOIL-AGROFORESTRY RESEARCH

1. Agroforestry systems can control erosion, thereby reducing losses of soil organic matter and nutrients.
2. Agroforestry systems can maintain soil organic matter at levels satisfactory for soil fertility.
3. Agroforestry systems maintain more favourable soil physical properties than agriculture, through a combination of organic-matter maintenance and the effects of tree roots.
4. Nitrogen-fixing trees and shrubs can substantially augment nitrogen inputs in agroforestry systems.
5. The tree component in agroforestry systems can increase nutrient inputs from the atmosphere and the B/C soil horizons.
6. Agroforestry systems can lead to more closed nutrient cycling, and so to more efficient use of nutrients.
7. Agroforestry systems offer opportunities to synchronize release of nutrients from decay of plant residues with requirements for uptake by crops.
8. The cycling of bases in tree litter can assist in reducing soil acidity, or checking acidification.
9. Agroforestry can be incorporated in systems for the reclamation of degraded soils.
10. In the maintenance of soil fertility under agroforestry systems, the role of roots is at least as important as that of above-ground biomass.

Soil observations in general agroforestry research

A component of soils research should form part of most agroforestry field trials, other than those directed at special aspects. It is fundamental to establish whether any proposed design, which is satisfactory in other respects, maintains the soil in a stable and productive condition; also it is desirable to gain some idea of the cycling of organic matter and nutrients.

The quantity and degree of sophistication of the measurements taken will vary according to facilities available and the nature of the agroforestry system under study. The following are suggested as a basic minimum of observations:

1. Before setting out a trial, take soil samples from the site, on a statistically based pattern, including from control plots, and have analyses carried

out. After three years, resample on a stratified design, based on components of the system, e.g., beneath and outside trees in mixed systems, or within hedgerows and crop alleys in hedgerow-intercropping systems. Repeat every three years, or when the trial is concluded. To reduce costs, only a proportion of the samples taken need be analysed in the first instance, the rest being done if the initial data indicate a likelihood of significant results.

2. Measure biomass production from all elements of the system, tree and crop, and its partitioning between leaf, fruit and wood. If possible, carry out analyses of the nutrient content of tree leaves and, preferably, other plant parts.
3. Make some attempt, however basic, to estimate root production and distribution. The simplest method is to cut a trench across selected tree-crop interfaces in the system and plot root distribution and mass.
4. If the trial is on sloping land, make some attempt to measure the rate of erosion. For samples taken from the eroded sediment, analyse organic matter and nutrient content.

Inclusion of such a set of basic soil observations in most trials could go far to provide, in five to seven years' time, the data needed to confirm on the basis of scientific evidence the potential of agroforestry for maintenance of soil fertility.

21. Research: a prototype demonstration plot in which hedgerow intercropping, using *Gliricidia sepium*, is coupled with grass strips and fruit trees. Maha Illuppallama, Sri Lanka.

22. Research: a tree/crop interface study, using *Leucaena leucocephala* with sorghum. Hyderabad, India.

23. Research: separating root interaction from above-ground effects by means of a buried polythene sheet. Hyderabad, India.

24. Research: a lysimeter for measuring leaching, with a tree growing on its soil. Dehra Dun, India.

Design of research

It would go beyond the scope of this review to discuss the design, techniques and problems of research in detail. It is hoped to make soil research in agroforestry the subject of a future ICRAF publication. A basis for rationalizing field studies is the distinction between rotational, spatial-mixed and spatial-zoned practices (Huxley, 1986a, 1986b) (p. 13). All that will be attempted here is to indicate the scope for design, and the relations between different levels of research, by means of two examples.

Erosion control under hedgerow intercropping

The apparent potential of hedgerow intercropping, or systems of contour-aligned hedges, to control soil erosion by water has been indicated above. The need is for a system that will reduce loss of nutrients and organic matter in eroded soil to acceptable levels. Control is achieved through a combination of the barrier effect of hedgerows and the cover effect of hedge prunings combined with crop residues. Design and management options exist in choice of hedgerow species, single or multiple hedgerows, within-row plant spacing, between-row spacing, and placement of prunings. Some of these options may be limited by acceptability to farmers, e.g. a requirement that prunings should be fed to livestock. There are very few existing experimental data. These needs and choices, within the framework of local conditions of climate, slope and soil, form the basis for the design of research (see Stocking, 1985a).

In this instance, it may be useful to include some system trials from the start, in view of the strong inferential evidence that success is likely. The first step is to design a prototype ('best bet') system, the second to test variations in selected variables. The design of the prototype could take into account considerations such as a hedgerow species with high survival and vigorous growth (as determined by basic multipurpose tree selection and evaluation, *not* as part of the erosion trials) and with moderate to slow leaf litter decay, to maintain soil cover during the period of erosive rains. Between-row spacing might in the first instance be made similar to that recommended for conventional conservation structures, for the climate, soil and slope angle. A prototype design based on these considerations could be set up on a plot of about 50 × 10 m (see below), possibly on two or more slope angles, and monitored for runoff volume, soil loss, and losses of organic matter and nutrients.

The time and cost required for multiple trials of complete systems is, however, considerable. Economy of effort can be made by including some *why*-level research, in this case studies of a single barrier hedge.

A possible design is shown in Figure 25. The assumption is that a suitable hedgerow species has been identified; the objective is to study the effects of barrier width, management of prunings and inter-row spacing, with the

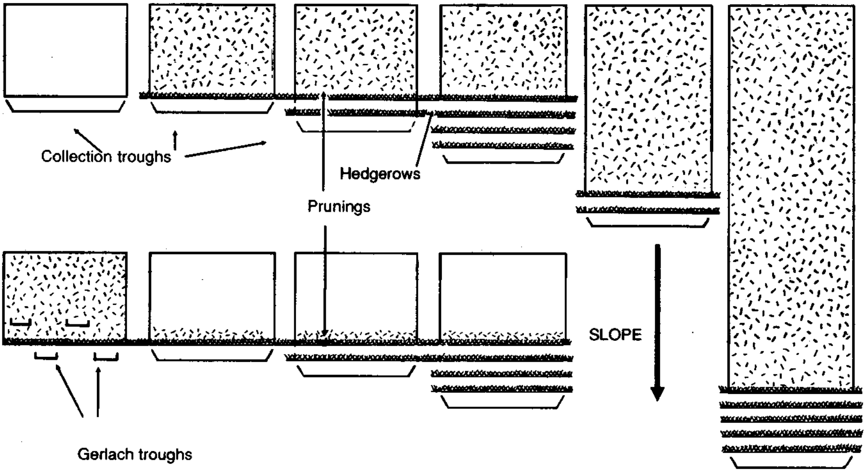


Figure 25. Treatments for studying the effects of a single hedgerow on runoff and erosion. Variables are the number of lines of hedge in a hedgerow, whether prunings are distributed across the cultivated land or laid against the hedgerow, and the width of the cultivated area. Randomization and replication are not shown.

aim of being able to design a system which combines erosion control with minimum planting effort or loss of land. The design consists of single, double and four-row hedgerows, each with two pruning treatments, laid across the alley or piled against the barrier, all with some standard width of cropped land upslope. Further plots test the double and four-row hedgerows with twice and four times the width of cropped land, plus a crop-only control. This gives nine plots in all, to be replicated as resources permit. If each plot is 5 × 5 m, plus 5 × 3 m for taking readings, one set of nine plots covers less land than a single system trial such as that outlined above. The results would permit design of a prototype system with considerably more confidence than is possible at present.

Most research stations would go no deeper than the above. However, some major sites should include some *how*-level research, in this case instrumenting a single hedgerow in such a way as to monitor subsurface as well as surface water flow, and actual sediment movement by means of tracer labelling, e.g. fluorescent or isotopic.

Soil organic matter maintenance by trees

The capacity of trees, shrubs or hedgerows to replace losses of soil organic matter is fundamental to maintenance of fertility under all types of agroforestry practice—rotational, spatial-mixed or spatial-zoned. The achievement of this capacity is therefore a fundamental element in design.

At the *what* level, monitoring of organic matter would be included as part of the standard package of observations in system trials. Details would vary according to whether rotational, spatial-mixed or spatial-zoned systems were being tested. Purely from the viewpoint of soil fertility, a large number of trees is desirable (e.g. closely spaced hedgerows or shade trees), and a compromise must be found with the smaller number required by considerations such as shading and crop area.

In order to be able to design practical systems other than by guesswork, however, it is necessary to find out the amounts and types of plant residues that are needed to maintain specified levels of soil organic matter under local conditions of climate and soil type. The basis for such research is to add combinations of different types and amounts of plant biomass and monitor the resulting soil changes. Since crop fruit will invariably be harvested, the relevant types of plant material are tree leaf (possibly plus fruit), wood and roots, and crop leaf (residues) and roots.

Unlike system trials, in which the totality of interactions is investigated, in *why*-level soils research it is desirable to eliminate or minimize microclimatic effects. This can be done by making all plots as nearly uniform as possible in this respect, or by regular and low pruning.

Some possible treatments are shown in Figure 26. Each plot is of a size sufficient to obtain reasonably uniform plant growth and permit repeated soil sampling, perhaps 5 × 5 m as a minimum; it should be surrounded by guard rows of the same plants and treatments. There are control plots of trees only (receiving tree leaf, wood and root residues), crops only (receiving crop leaf and root residues), and an area tilled but with neither trees nor crops. This last is called a 'kill SOM' plot, the aim being to follow the rate of loss of soil organic matter (SOM) without renewal from any source.

For other treatments, tree and crop above-ground residues can be included or excluded by manual transfer of prunings and litter. Root residues from adjacent plants can be excluded by buried plastic sheets parallel to hedgerows or, less easily, surrounding individual trees. It may be useful to include amounts of plant material greater than that likely to be obtainable in practical systems, the better to establish the functioning of processes.

The lower block in Figure 26 is for comparison with a rotational system. The proportion of trees to crops is the same as in some of the spatial plots, perhaps 25% of the total area. The block of trees is rotated around the area at two- or three-year intervals, cropping the remaining part. Such a comparison between spatial systems and rotational systems, with the same proportions of tree and crop but substituting interactions over time to those in space, is a valuable feature in many kinds of agroforestry research besides studies of soil fertility. Plots are sampled annually to monitor changes in soil organic matter, together with soil physical and chemical conditions and crop yield.

The *how* level of research in this case might be based on carbon-14 isotope labelling, following the fate of different kinds of plant residue added to the soil.

The same approach, the combination of system trials with studies of the critical elements of the system, can be applied to nutrient cycling and other aspects of soil fertility.

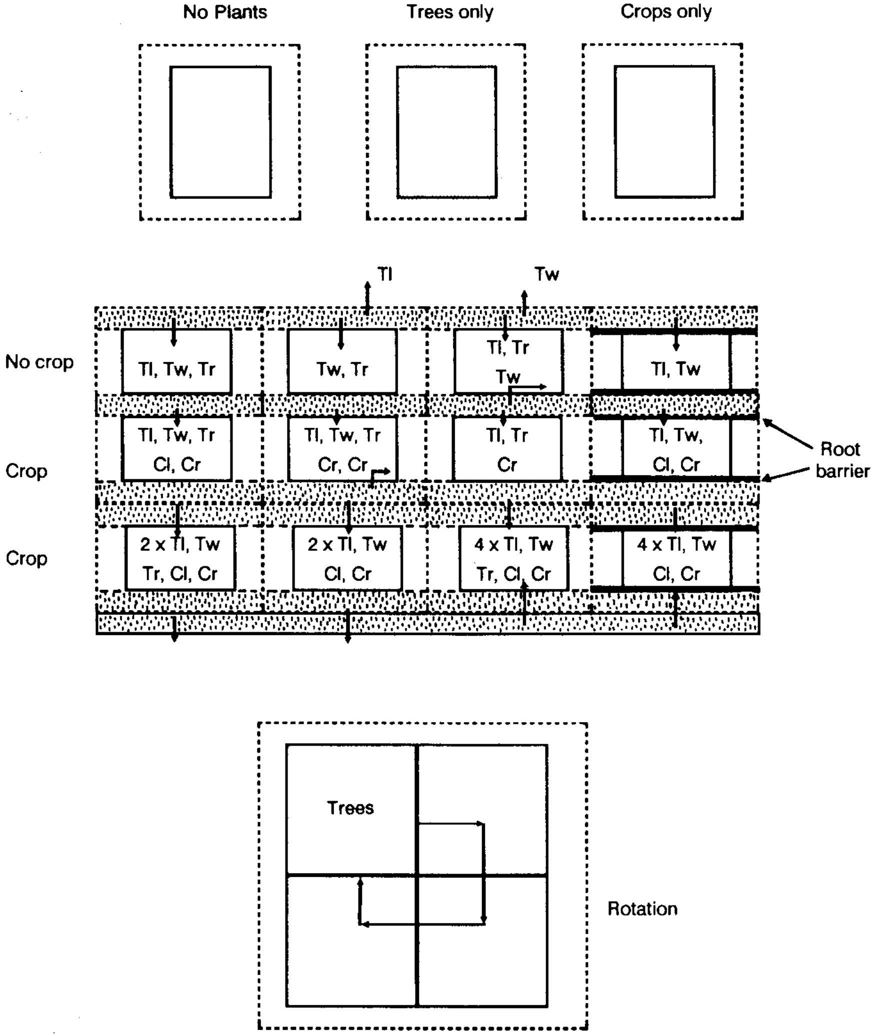


Figure 26. Treatments for studying the effects of tree and crop residues on soil organic matter. Letters indicate which plant residues are applied to the soil, as follows: T = tree, C = crop, l = leaf, w = wood, r = root, 2 × = at twice the standard rate, 4 × = at four times the standard rate. Randomization and replication are not shown.

Techniques and observations

Many of the observations and assumptions made in agroforestry are similar to those in agricultural research. Others require adaptation to the special circumstances of tree and crop components.

For soil-erosion research, the former standard US plot, 20 × 2 m (0.01 acres), is no longer universal in agricultural studies and presents problems in agroforestry. It is too small to obtain sufficiently homogeneous, or representative, coverage in mixed tree-crop systems. A few plots of this size may be included to permit comparison with the large body of existing data based upon it. Larger plot sizes are currently in use for most agroforestry system trials, for example at Dehra Dun, India (90 × 15 m), Ibadan, Nigeria (70 × 10 m), Machakos, Kenya (40 × 40 m) and Maha Illuppallama, Sri Lanka (100 × 40 m).

The plot approach to erosion measurement is complemented by first-order catchment studies recording runoff and sediment content at an outlet flume. It is of the utmost importance that measurements should include analysis of the organic matter and nutrient content of eroded material, in addition to the mass of soil lost.

For research into soil fertility, many observations are the same as in agricultural trials. A useful basic set of methods of analysis is given in the methods handbook of the Tropical Soil Biology and Fertility programme (Anderson and Ingram, 1989). Five aspects may be emphasized:

1. It is fundamental to measure all rates of biomass production, by tree and crop components, partitioned into leaf, fruit, wood and roots; to record all additions and removals of organic matter to and from the plot or system under study; and where possible, to analyse samples of these plant parts for their nutrient content.
2. As a special case of the above, some attempt should be made to measure standing biomass and production of root systems, in view of their importance to the organic-matter and, probably, nutrient economies. Methods are given in Anderson and Ingram (1989).
3. Monitoring should cover both soil properties and plant growth. To measure soil changes alone is insufficient: the properties determined in soil analysis are individual variables, in some cases artificial, and may not fully indicate soil fertility. Conversely, if plant growth (or even crop yield) is taken as the sole criteria for evaluation, then the research falls entirely into the 'what happens' level. The soil is then treated as a 'black box', and one has no evidence about causes of the observed effects.
4. Micro variability of properties in space is a severe problem in all kinds of soil research. It is not only that substantial soil changes can occur over distances of a few metres. Additional to such variation, samples of a soil which appears completely uniform show coefficients of variation in analytical values of the order of 25% for carbon and nitrogen and 30

to 70% for other nutrients (Dent and Young, 1981, pp. 92–95). To identify significant changes requires substantial numbers of samples (Cochrane and Cox, 1957, pp. 20–21). Use of composite sampling can reduce the costs of analysis.

5. Most agroforestry research is environment specific Young, 1986b. It cannot be assumed that a practice or system which is effective in one combination of climate, landforms, soil and vegetation will be equally effective in another. Thus each practice needs to be tested for the major climatic zones, the main soil types present and, where relevant (sylvopastoral systems), for vegetation types.

Chapter 17
Conclusion

Previous reviews

In the major previous review of soil productivity under agroforestry, Nair (1984 pp. 68–69, 72) concluded that:

> The inclusion of compatible and desirable species of woody perennials on farmlands can result in a marked improvement in soil fertility.... Agroforestry is only one potential approach to land use, which, if adopted properly, may prove superior to some other use approaches in some situations.... Properly practised, the system is likely to use the nutrients more efficiently and cost effectively, and to increase the sustainability of production from the land.... [However,] the concepts have to be validated by field research before site-specific soil management practices can be recommended.

Reviewing the effects of tropical agroforestry systems on soil erosion by water, Wiersum (1984, pp. 231,237) found that:

> Individual trees cannot be expected to exert the same protective effect as undisturbed forest ecosystems. The key to controlling erosion in agroforestry does not lie in the presence of trees themselves, but rather in good management practices.... Such management practices do not only include methods of maintaining a direct soil cover, but may also entail structural measures such as terracing.

In a recent account of soil productivity and sustainability under agroforestry systems, Sanchez (1987, pp. 206, 219) gave as the basic soil-agroforestry hypothesis:

> Appropriate agroforestry systems improve soil physical properties, maintain soil organic matter, and promote nutrient cycling.... While evidence exists for the beneficial effects on soils of certain agroforestry technologies (especially on more fertile soils), there is a tendency for over-generalization and extrapolation of soil productivity and sustainability benefits to other

> more marginal sites. The time has come to bring science into the picture and systematically test the effects of agroforestry systems on different soils, and vice versa.

Each of these conclusions combines, in different ways, acceptance of a potential with words of caution. For Nair, writing before the existence of appreciable agroforestry research, it is that the concepts have to be validated before they can be recommended in the field. Wiersum warns that agroforestry does not automatically control erosion, but only with good design and management. Sanchez's proviso is that optimistic findings of a few experimental studies to date should not be uncritically extended to all soil types and agroforestry practices.

The present review

The conclusion from the present study is similar to those of the above reviews, but differs in emphasis. By including the control of erosion, the general soil-agroforestry hypothesis can be stated as follows:

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

Appropriate means suited to the physical environment and to social and economic conditions, properly designed and well managed. The achievement of such designs requires a proper foundation of research.

The evidence available is of two kinds, direct and indirect. Direct evidence, based on studies of the effects of agroforestry systems upon soils, is at present sparse, but almost invariably supports the basic hypothesis. In addition, there is much indirect evidence, drawn from agriculture, forestry and soil science, of the beneficial effects of trees on soil fertility and the potential to make use of this capacity in agroforestry systems.

Taking these two kinds of evidence together, it is concluded that the general soil-agroforestry hypothesis is essentially true. There is a con-

THE GENERAL SOIL-AGROFORESTRY HYPOTHESIS

Appropriate agroforestry systems have the potential to:

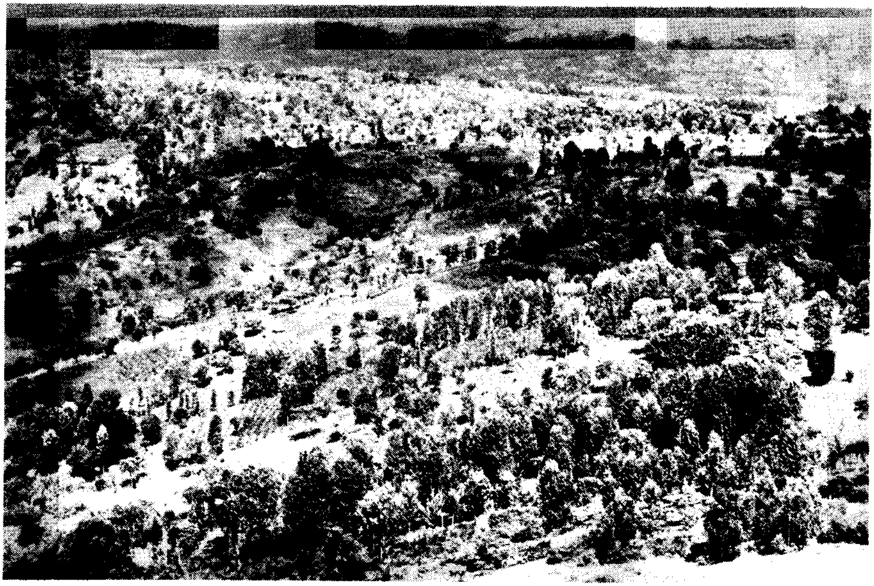
- control erosion
- maintain soil organic matter and physical properties
- promote efficient nutrient cycling.

It is concluded that this hypothesis is essentially true, and applicable to a wide range of environmental conditions.

siderable potential for soil conservation through agroforestry, both in control of erosion and by other means of maintaining soil fertility. This potential applies to the majority of agroforestry practices, and over a wide range of climatic zones and soil types. Those agroforestry practices with a specific potential for soil conservation are given in Table 33.

Table 33. *Agroforestry practices with potential for soil conservation.*

Agroforestry practice	Control of erosion	Maintenance or improvement of fertility
Improved tree fallow		+
Trees on cropland		+
Plantation crop combinations	++	++
Multistorey tree gardens	++	++
Hedgerow intercropping	++	++
Trees on erosion-control structures	++	
Windbreaks and shelter-belts	++	+
Trees on pastures	(+)	++
Reclamation forestry leading to multiple use	++	++



25. Farming landscape with trees. Embu, Kenya.

One major qualification to this conclusion, arising from the scope of the present study, is that it does not take into account availability of soil water. This is frequently a limiting factor for plant growth in dry subhumid and semi-arid environments, and a large research effort is needed into soil-water processes under agroforestry. This will need to combine evidence drawn from research in soil physics, agriculture and forestry with experimental studies of soil-water interactions at the tree-crop interface and under agroforestry systems. A starting point is set by a recent symposium on applications of meteorology to agroforestry (Darnhofer and Reifsnyder, 1989).

A second qualification is that already noted, the paucity of experimental evidence. To confirm the apparent potential, and to permit the design of agroforestry systems suited to specific environments, a major research effort is called for.

If research succeeds in confirming the hypotheses and conclusions reached from the limited evidence currently available, then agroforestry has the potential to make a major contribution to soil conservation and sustainable land use.

SUMMARY

The following is a summary of the conclusions reached in this review. Summaries also have been given in Young (1987b, and in press, a). 'Trees' refers to all woody perennials, including trees, shrubs and bamboos. 'Crops' includes both agricultural crops and pastures.

Part I. Soil Conservation and Agroforestry

Soil conservation and sustainability

Sustainability refers to productivity combined with conservation of the natural resources on which production depends. Maintenance of soil fertility forms a major component of sustainable land use.

The primary objective of *soil conservation* is maintenance of soil fertility. To achieve this, control of erosion is one necessary, but by no means sufficient, condition. Equally important are maintenance of the physical, chemical and biological soil conditions that are favourable for plant growth.

Agroforestry

Agroforestry refers to land-use systems in which trees or shrubs are grown in association with crops (agricultural crops or pastures), in a spatial arrangement or a rotation, and in which there are both ecological and economic interactions between the trees and other components of the system.

An *agroforestry practice* is a distinctive arrangement of components (e.g. trees, crops, pastures, livestock) in space and time. An *agroforestry system* is a specific local example of a practice. There are thousands of agroforestry systems, traditional and modern, but only some 20 distinct practices. Thus, agroforestry offers a wide range of choice, giving opportunities to design systems suited to a variety of physical environments and social and economic conditions.

Agroforestry practices and systems can be classified according to their components and their temporal and spatial arrangement. The division into *rotational, spatial-mixed* and *spatial-zoned practices* is related to the types and degrees of interaction between tree and crop components, and forms a basis for research (see Table 4, p. 12).

Management options for restoring or maintaining soil fertility may be constrained by:

- type of land: the option is only applicable on land of certain kinds
- extent of land: the option requires land additional to that under cultivation
- supply problems: availability or cost of inputs.

Most non-agroforestry methods suffer from one or more of these constraints. The various agroforestry practices are applicable to a wide range of environmental conditions and do not require inputs that are in short supply or costly. The land requirements of the tree component may be compensated either by higher crop yields or by the value of products from the tree. Thus, agroforestry is widely applicable as a practical management option. One of its greatest potentials is to help solve land-use problems in areas of sloping land.

Part II. Agroforestry for Control of Soil Erosion

Trends in soil-conservation research and policy

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

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

Aspects of these recent trends significant to agroforestry are:

- The potential of agroforestry for erosion control should be considered jointly with that for maintenance of fertility.
- Particular attention should be given to the capacity of tree litter to maintain soil cover.
- It is important to develop agroforestry systems with the potential for sustainable land use on sloping lands.
- Through its capacity to combine production with conservation, agroforestry offers a means of securing the cooperation of farmers.

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

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

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

The barrier and cover approaches to erosion control

Erosion can be controlled through checking downslope flow of water and entrained soil by means of barriers to runoff, the *barrier approach*, and through maintenance of a ground surface cover of living plants and litter, the *cover approach*. The effect of soil cover is both to check raindrop impact and to provide dispersed micro-barriers to runoff.

Models for the prediction of erosion are based on the controlling variables of rainfall erosivity, soil erodibility, slope (angle and length) and soil cover. A review of these models shows that there are equal or greater opportunities to reduce erosion by means of the cover approach than by the barrier approach.

Experimental evidence

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

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

- Rainfall erosivity is often reduced only slightly (by the order of 10%), and may sometimes be increased, by the presence of a tree canopy.
- The resistance of the soil to erosion, which commonly decreases under continuous arable use, can be sustained through the capacity of agroforestry to maintain soil organic matter.
- Reduction of runoff, and thereby of effective slope length can be achieved firstly by means of barrier hedgerows, and secondly by combining trees with earth structures.
- As noted above, there is a considerable potential to increase soil cover by means of plant litter.

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

The presence of trees does not necessarily lead to low rates of erosion. What matters is the spatial arrangement of the trees and, especially, the way in which they are managed.

Data on recorded erosion rates under agroforestry are sparse, although more measurements are in progress. The limited existing data support the hypothesis that agroforestry systems have the potential to reduce erosion to acceptable rates.

Hedgerows differ from ditch-and-bank structures in that they are partly permeable barriers. Standard criteria for design of conservation works, based on impermeable earth barriers, are not necessarily transferable without modification to barrier hedges. An advantage arising from partial permeability is that hedgerow barriers are less likely to be destroyed during heavy storms. Research is needed into the effects of hedgerow barriers on runoff and soil movement.

Agroforestry practices for erosion control

The role of trees and shrubs in erosion control may be direct or supplementary. In *direct use*, the trees are themselves the means of checking runoff and soil loss. In *supplementary use*, control is achieved primarily by other means (grass strips, ditch-and-bank structures, terraces); the trees serve to stabilize the structures and to make productive use of the land which they occupy.

The functions of the tree component in erosion control may include any of the following:

- to reduce water erosion by a surface litter cover
- to act as a runoff barrier by closely planted hedgerows, coupled with the litter that accumulates against them
- to prevent decline in soil-erosion resistance, through maintenance of organic matter
- to strengthen and stabilize earth-conservation structures where present
- to reduce wind erosion by windbreaks and shelterbelts (not reviewed here)
- to make productive use of the land taken up by conservation structures
- to serve the function, partly psychological, of helping to link erosion-control practices with production, thereby making these an integral and permanent part of the farming system.

Methods of erosion control through agroforestry have been designed, recommended or are being tried in a number of countries, in some cases on the basis of experimental results, at other sites on an empirical or trial basis.

Firm knowledge of the effects of agroforestry practices on erosion is sparse. On the basis of such data as exist, the probable effects may be summarized as follows (see Table 10, p. 76).

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

Spatial-mixed practices. Plantation crop combinations and *multistorey tree gardens*, including home gardens, can control erosion through the provision of a dense, regularly renewed, ground surface cover. In the case of multistorey gardens, such control is intrinsic to the nature of the practice. For plantation crop combinations, control depends on management, specifically the maintenance of a ground cover of litter.

Spatial-zoned practices. For *hedgerow intercropping* (alley cropping, barrier hedgerows) there is substantial inferential, and limited experimental, evidence of potential erosion control through provision of a litter cover on the cropped alleys and a barrier function through the hedgerows. Effective erosion control will not be automatic, and will vary with detailed design and management practices. Given the apparently high potential coupled with the sparsity of experimental data, there is an urgent need for controlled measurements of erosion rates under this practice.

The practice of *trees on erosion-control structures* involves the supplementary use of the tree component. Tree planting can make productive use of the land occupied, help to stabilize the structures and in some cases add to their protective effects. It also fulfils a psychological function, making it more likely that the structures will be perceived as beneficial and thus maintained. This applies to trees on ditch-and-bank structures, grass barrier strips, and terraces.

Although not covered in this review, the established potential of *windbreaks and shelterbelts* to control wind erosion may be noted for completeness.

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

Reclamation forestry and watershed management. There are opportunities to integrate agroforestry with the known benefits of *reclamation forestry*. A period of reclamation is followed by controlled productive use, retaining part of the tree cover for continued conservation.

Agroforestry can form a component, together with other major kinds of land use, in *integrated watershed management.*

Part III. Agroforestry for Maintenance of Soil Fertility

Soil fertility and degradation

Soil fertility is the capacity of soil to support the growth of plants, on a sustained basis, under given conditions of climate and other relevant properties of land. It is part of the wider concept of land productivity.

Diagnosis of the problem of low crop yields should distinguish between low soil fertility, caused by natural soil conditions, and decline in soil fertility, brought about by past land use. These two causes may call for different kinds of action.

Effects of trees on soils

The association between trees and soil fertility is indicated by the high status of soils under natural forest, their relatively closed nutrient cycles, the soil-restoring power of forest fallow in shifting cultivation, and the success of reclamation forestry. More detailed evidence is provided by comparisons of soil properties beneath and outside tree canopies.

Trees maintain or improve soils by processes which:

- augment additions of organic matter and nutrients to the soil
- reduce losses from the soil, leading to more closed cycling of organic matter and nutrients
- improve soil physical conditions
- improve soil chemical conditions
- affect soil biological processes and conditions.

Some of these processes are proven, others are hypotheses in need of testing (see Table 14, p. 97; Figure 7, p. 98).

Soil organic matter

Soil organic matter plays a key role in maintaining fertility, particularly, but not only, under low-input conditions. Its main effects are to improve soil physical properties and to provide a reserve of nutrients, progressively released by mineralization.

Herbaceous plant residues applied to the soil initially decompose rapidly, with a half-life in tropical soils of less than six months. Woody residues decompose more slowly. During decomposition there is a loss of carbon and a release of nutrients. The remaining material becomes soil organic matter or humus. There are at least two fractions of humus, labile and stable. It is largely the labile fraction which contributes to nutrient release, and which is directly affected by management. It is not known whether woody residues confer distinctive properties on soil humus.

Taking as a basis the established cycling of organic matter under natural forest and decline under cultivation, it is feasible to construct a cycle under agroforestry which maintains equilibrium in soil organic matter. The following are approximate rates of above-ground biomass production which, if returned to the soil, can be expected to maintain organic matter at levels acceptable for soil fertility:

Humid tropics	8000 kg DM/ha/yr
Subhumid tropics	4000 kg DM/ha/yr
Semi-arid zone	2000 kg DM/ha/yr.

The net primary production of natural vegetation communities is somewhat higher than these values, whilst that from trees used in agroforestry can approach, and occasionally exceed, that from natural vegetation (see Table 20, p. 22).

In agroforestry systems, the requirements to maintain soil organic matter can certainly be met if all tree biomass and crop residues are added to the soil. If the woody part of the tree is harvested, this becomes more difficult, and it is impossible if tree foliage and crop residues are also removed.

The rate of litter decay is influenced by its quality, or relative content of sugars, nutrient elements, lignin and other polyphenols. Rates of decay determine the timing of nutrient release. It is desirable to synchronize nutrient release with plant uptake requirements. Agroforestry systems offer opportunities to manipulate this release, through selection of tree species and timing of pruning.

Plant nutrients

Nitrogen-fixing trees and shrubs, growing within practical agroforestry systems, are capable of fixing about 50–100 kg N/ha/yr. The nitrogen returned in litter and prunings may be 100–300 kg N/ha/yr, partly derived by recycling of fertilizer nitrogen (see Table 22, p. 131).

The second major role of trees is to improve the efficiency of nutrient cycling. Mechanisms are uptake from lower soil horizons, reduction of leaching loss by tree-root systems, balanced nutrient supply, and improvement in the ratio between available and fixed minerals. For a tree-leaf biomass production of 4000 kg DM/ha/yr, the potential nutrient return in litter, as kg/ha/yr, is of the order of 80–120 for nitrogen, 8–12 for phosphorus, 40–120 for potassium and 20–60 for calcium. These amounts are substantial in relation to the nutrient requirements of crops (see Table 23, p. 136; Figure 12, p. 132; Figure 13, p. 134).

In research, the emphasis on nitrogen fixation has led to a comparative neglect of the effects of agroforestry systems on other nutrients, and on the potential to achieve more closed cycles of all nutrients under agroforestry as compared with agriculture.

Other soil properties and processes

There is substantial evidence that trees in agroforestry systems can help to maintain soil physical properties, a major element in soil fertility.

The base content of tree litter can help to check acidification. It is unlikely to be of sufficient magnitude appreciably to moderate the acidity of strongly acid soils, other than in systems which make use of tree biomass accumulated over many years.

As a means of forest clearance, manual and shear-blade methods leave the soil in better condition than bulldozer clearance. The efficiency of rotational systems is necessarily reduced if burning is practised, with consequent loss of most stored carbon, nitrogen and sulphur.

As shown in Part II of this review, agroforestry has a potential for control of soil erosion. Since the major adverse effect of erosion is loss of organic matter and nutrients, the potential to control erosion constitutes a major means of maintaining soil fertility.

The role of roots

There has recently been increasing recognition of the importance of roots as a component of primary production. Root biomass of trees is typically 20–30% of total plant biomass (or 25–43% of above-ground biomass). However, net primary production of roots is substantially more than standing biomass, owing to the turnover of fine roots. Roots form an appreciable store of nutrients, and since they are almost invariably returned to the soil, constitute a substantial element in nutrient recycling.

Tree root systems, together with their associated mycorrhizae, improve the efficiency of nutrient cycling, defined as the ratio between plant uptake and losses by leaching and erosion. They also contribute to soil physical properties.

The key to making use of root and mycorrhizal systems in agroforestry lies in maximizing these positive effects whilst reducing tree-crop competition for moisture and nutrients. There is a clear need for more knowledge of root growth and functioning in agroforestry systems.

Trees and shrubs for soil improvement

The properties which constitute a good soil-improving tree, and thus the means of recognizing one, are not well established. The following are contributory:

- high nitrogen fixation
- high biomass production
- a dense network of fine roots or associated mycorrhizae
- some deep roots
- high, balanced nutrient content in the foliage
- appreciable nutrient content in the roots
- either rapid litter decay, where nutrient release is desired, or a moderate rate of litter decay, for protection against erosion
- absence of toxic substances in foliage and root exudates
- for reclamation or restoration, a capacity to grow on poor soils.

Fifty-five tree and shrub species, belonging to 32 genera, are identified which have a potential to maintain or improve soil fertility (Table 27, p. 159). Species with particularly high potential include:

- *Acacia albida*
- *Acacia tortilis*
- *Calliandra calothyrsus*
- *Casuarina equisetifolia*
- *Erythrina poeppigiana*
- *Gliricidia sepium*
- *Inga jinicuil*

- *Leucaena leucocephala*
- *Prosopis cineraria*
- *Sesbania sesban.*

Agroforestry practices for soil fertility

Most reported indigenous agroforestry systems (other than shifting cultivation) have a spatial-mixed structure, in contrast to the spatial-zoned systems which are the focus of much current research. In the majority of indigenous systems, control of erosion, maintenance of fertility, or both, are an identified function. Use of poor soils and reclamation of degraded land are also found (see Table 28, p. 170).

A substantial body of research results on soil exists only for shifting cultivation and the plantation-crop combination of coffee or cacao with combinations of *Erythrina, Inga* and *Cordia.* Data on hedgerow-intercropping systems come mainly from one site, at Ibadan, Nigeria, although further studies are in progress or planned. Soils data on other agroforestry practices are sparse.

Results from soils research on agroforestry practices include the following.

Rotational practices. For *shifting cultivation*, dependent on natural forest fallow, there is no way of escaping the large land requirement implied by the fallow-to-cropping ratio necessary to restore soil fertility. Owing to population pressure upon land, this formerly stable system is no longer sustainable in many areas.

The potential of *improved tree fallows*, and more generally the relative effects on soils of rotational and spatial combinations of trees and crops, are not known.

Spatial-mixed practices. Plantation crop combinations of coffee or cacao with *Erythrina, Inga* and *Cordia* are characterized by a large return of organic matter and nutrients to the soil, in litter and prunings, together with a moderate level of nitrogen fixation. Where fertilized, the nutrient return includes nutrients in fertilizer, demonstrating the efficiency of the system in promoting nutrient retrieval and recycling.

Multistorey tree gardens, including home gardens, through a high rate of biomass production and efficient nutrient recycling, exemplify conditions of sustainability, by combining high productivity with complete conservation of resources.

Spatial-zoned practices. In *hedgerow intercropping* (alley cropping), a large biomass production can be obtained from hedgerows, together with nitrogen fixation and substantial return of nutrients in prunings. It may be possible to design systems in which crop yields, per unit of total area, are greater with hedgerows than in monocropping. The one available soil-monitoring study showed successful maintenance of fertility for six years. Roots are probably a contributory factor (see Table 32, p. 000).

The presence of a given agroforestry practice is by no means sufficient to ensure maintenance of soil fertility. Equally important are: (1) the design of the system in relation to local environmental and socio-economic conditions; (2) good management of the system; (3) the integration of agroforestry with the farming system as a whole.

Part IV. Agroforestry for Soil Conservation

Modelling soil changes under agroforestry

A computer model has been developed, Soil Changes Under Agroforestry (SCUAF), to predict the effects on soils of specified agroforestry systems within given environments. This is a relatively simple input-output model, covering prediction of changes in erosion, soil organic matter and nutrients. Illustrative outputs are given in Figures 19–23 (pp.209–211). The SCUAF model can be used as an aid to the design of agroforestry research.

The need for research

In less-developed countries of the tropics and subtropics, there is a large and growing problem of decline in soil fertility. This is caused both by erosion and by other processes of soil degradation. Indirect evidence, together with limited experimental data, indicate that many agroforestry practices have the potential both to control erosion and to check other forms of soil degradation. The combination of a high apparent potential with a scarcity of experimental results points clearly and strongly to the need for research.

Agroforestry research can be conducted at three levels: 'What happens?' or trials of systems, 'Why does it happen?' or studies of elements within systems or interactions between components, and 'How does it happen?' or studies of basic processes. Trials of systems alone (*what* research) are inefficient as a means of advancing knowledge, owing to the large number of variables and the site-specific weather and soil conditions. Studies of elements within systems (*why* research) lead towards the efficient design of prototype systems, which can then be tested over a limited range of variation. A better knowledge of basic processes will help in understanding the functioning of components, their interactions and thereby systems.

Research into soil conservation by means of agroforestry can be considered in two parts: specialized studies and soil aspects of general agroforestry research. Subjects for specialized soil research are listed, together with a suggested minimum set of soil observations to be included in general agroforestry research. A set of ten hypotheses for investigation by specialized soil-agroforestry research is presented p. 218.

Examples of research designs at the *why* level are given, together with notes on experimental techniques and observations. Further studies of research methods specific to the problems of agroforestry are required.

Conclusion

The general soil-agroforestry hypothesis is that:

Appropriate agroforestry systems control erosion, maintain soil organic matter and physical properties, and promote efficient nutrient cycling.

It is concluded that this hypothesis is essentially true. There is a considerable potential for soil conservation through agroforestry, both in control of erosion and by other means of maintaining soil fertility. This potential applies to many agroforestry practices and over a wide range of climatic zones and soil types (see Table 33, p. 231).

If research succeeds in confirming this conclusion, then agroforestry has the potential to make a major contribution to soil conservation and sustainable land use.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACIAR: Australian Centre for International Agricultural Research (Canberra, Australia)

AGLS (FAO): Agriculture Department, Land and Water Development Division, Soil Resources, Management and Conservation Service (Rome, Italy)

ASA: American Society of Agronomy (Ankeny, Iowa, USA)

ASAE: American Society of Agricultural Engineers (St. Joseph, Michigan, USA)

BOSTID: Board of Science and Technology for International Development (Washington, DC, USA)

CAB International: Commonwealth Agricultural Bureaux International (Wallingford, UK)

CATIE: Centro Agronómico Tropical de Investigación y Enseñanza (Turrialba, Costa Rica)

CAZRI: Central Arid Zone Research Institute (Jodphur, India)

CIAT: Centro Internacional de Agricultura Tropical (Cali, Colombia)

CREAMS: Chemicals, Runoff and Erosion from Agricultural Management Systems

CTFT: Centre technique forestier tropical (Nogent-sur-Marne, France)

D.R.S.–C.E.S.: Défense et restauration des sols–conservation des eaux et du sol

EDI: Energy Development International (Washington, DC, USA)

EPIC: Erosion Productivity Impact Calculator

EWC: East West Center (Honolulu, Hawaii, USA)

FAO: Food and Agricultural Organization of the United Nations (Rome, Italy)

FONC Project: Forest/Nature/Conservation Project (Jojakarta, Indonesia)

FR Germany: Federal Republic of Germany

GEMS (UNEP): Global Environmental Monitoring System (Nairobi, Kenya)

GTZ: Gesellschaft für technische Zusammenarbeit (Eschborn, Federal Republic of Germany)

IAEA: International Atomic Energy Agency (Vienna, Austria)

IAHS: International Association of Hydrological Sciences (Wallingford, UK)

IBP (UNESCO): International Biological Programme (Paris, France)
IBSRAM: International Board for Soil Research and Management (Bangkok, Thailand)
ICAR: Indian Council of Agricultural Research (New Delhi, India)
ICRAF: International Council for Research in Agroforestry (Nairobi, Kenya)
ICRISAT: International Crop Research Institute for the Semi-Arid Tropics (Hyderabad, India)
IDRC: International Development Research Centre (Ottawa, Canada)
IFAD: International Fund for Agricultural Development (Rome, Italy)
IITA: International Institute of Tropical Agriculture (Ibadan, Nigeria)
ILCA: International Livestock Centre for Africa (Addis Ababa, Ethiopia)
ILO: International Labour Organization of the United Nations (Geneva, Switzerland)
ILRI: International Institute for Land Reclamation and Improvement (Wageningen, Netherlands)
INEAC: Institut national pour l'étude agronomique du Congo (Kisangani, Zaire)
IRRI: International Rice Research Institute (Los Baños, Philippines)
ITC: International Institute for Aerospace Survey and Earth Sciences (Enschede, Netherlands)
IUFRO: International Union of Forestry Research Organizations (Vienna, Austria)
NFTA: Nitrogen-Fixing Tree Association (Waimanalo, Hawaii, USA)
NIFTAL: Nitrogen Fixation of Tropical Agricultural Legumes project (Paia, Hawaii, USA)
ORSTOM: Institut français de recherche scientifique pour le développement en coopération (Paris, France)
SADCC: Southern African Development Coordination Committee (Gabarone, Botswana)
SIDA: Swedish International Development Authority (Stockholm, Sweden)
SLEMSA: Soil-Loss Estimation Model for Southern Africa
TSBF: Tropical Soil Biology and Fertility programme (Harare, Zimbabwe)
UK: United Kingdom
UNEP: United Nations Environment Programme (Nairobi, Kenya)
UNESCO: United Nations Educational, Scientific and Cultural Organization (Paris, France)
UNFPA: United Nations Fund for Population Activities (New York, NY, USA)
UPLB: University of the Philippines at Los Baños (Los Baños, Philippines)
USA: United States of America
USAID: United States Agency for International Development (Washington, DC, USA)

USDA: United States Department of Agriculture (Washington, DC, USA)
USLE: Universal Soil-Loss Equation
VAM: vesicular arbuscular mycorrhizae
WMO: World Meteorological Organization (Geneva, Switzerland)

INDEX

Agroforestry covers land use systems in which trees and shrubs are grown in association with herbaceous crops, either in a spatial arrangement or a rotation. It has productive functions, such as the capacity of the tree component to produce fuelwood, fodder and fruit, and service functions, chief among which is that of soil conservation. Soil conservation is treated here in its wider sense, to include both control of erosion and maintenance of fertility. In the current search for sustainability, which involves the combination of production with conservation of the resources on which that production depends, soil conservation plays a major role.

This book is a review of the potential of agroforestry to contribute to soil conservation. Its aims are to summarize the present state of knowledge, including both known capacity and apparent potential, and to indicate the needs for research. The overall conclusion is that appropriate agroforestry systems have the potential to control erosion, maintain soil organic matter and physical properties, and promote efficient nutrient cycling. This applies to a wide range of climatic zones and soil types. There is an urgent need for research to acquire further experimental evidence to support this conclusion. Many obstacles, social and economic as well as technical, need to be overcome if the potential is to be fulfilled. If this effort is successful, then agroforestry can make a major contribution to sustainable land use.

Anthony Young is a Principal Scientist with ICRAF and formerly Professor of Environmental Sciences at the University of East Anglia, Norwich, U.K., where he was awarded the degree of Doctor of Science for contributions to the study of tropical soils and land evaluation. Trained as a geographer and soil scientist, his work has been divided between university-based research into problems of natural resource development and practical contributions to resource-use planning in developing countries of Africa and Asia. He was a member of the FAO team responsible for development of methods of land evaluation for agriculture and forestry. He has over 100 scientific publications, including books on *Tropical soils and soil survey* (1976) and *Soil survey and land evaluation* (1981).