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Soil Fertility Review for Forest / Agriculture Interface.

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FINAL TECHNICAL REPORT

Soil Fertility Review for Forest/Agriculture Interface

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Executive summary

1. The review was commissioned by NRI to review the literature on soil fertility with regard to the forest/agriculture interface system.

2. The review demonstrates the complexity and diversity of the forest/agriculture interface. The interface includes a wide range of activities in which the relative proportions of crops and trees vary temporally and spatially and in which the level of external inputs varies considerably.

3. Many smallholder systems include no external inputs so their ability to sustain agriculture is dependent on the inherent fertility of the soil, the ability of tree roots to extract deep nutrients, and depending on species, biological nitrogen fixation. Because the predominant soils of the tropics are Oxisols and Ultisols with low inherent fertility, crop production can only be maintained for short periods without inputs of nutrients.

4. The 5 most important areas for research are:

   a) Development of integrated systems of organic and inorganic fertilisation.
   b) Determination of P dynamics in tropical soils and possible sources of P inputs.
   c) Investigation of the interactions between crop and tree roots so that closed cycling of nutrients can be effectively promoted.
   d) Long-term studies of organic matter decomposition in tropical soils and the release of mineralised nutrients.
   e) The use of trees in fallow periods to determine the most effective temporal distributions.

Background

Considerable emphasis is placed within the Forest/Agriculture interface programme on reducing fragility and enhancing fertility of cultivated soils within the system. Two of the three prescribed outputs from two of the purposes highlight this issue.

Previous research and recent publications have stressed the possible advantages of trees in enhancing the fertility of soils for subsequent crop production and also for ameliorating soil physical conditions. This review was commissioned so that existing knowledge could be summarised before further research on these topics is undertaken by NRI-financed contracts.

Project purpose

To review the existing knowledge and literature on soil fertility issues associated with the forest/agriculture interface by climatic zone and major soil type.

Research activities

The major activity in this project was to collate and summarise the existing literature on fertility issues at the forest/agriculture interface. This was done initially by a search of the CABI database and followed up with a day visit to the Oxford Forestry Institute to meet with researchers there and with a 10-day visit to ICRAF, Kenya. The visit to Kenya was particularly useful in obtaining recent, unpublished reports and in ordering priorities for research.

The final report was drafted by the research assistant and then revised by Dr Nortcliff and Prof. Gregory.

Outputs

An initial report was submitted to NRI at the end of November 1995 and revised in early 1996 following comments from Dr Ian Hunter. The revised report was submitted in March 1996. The report reviews existing published and "grey" literature collected from ICRAF, Kenya and identifies 13 research needs in 3 broad areas of soil nutrients, roots, and soil organic matter.

Contribution of outputs

The purpose of the project was achieved by the activities and outputs listed in the original logical framework. The report produced for NRI identifies key gaps in knowledge and suggests future priorities for research.

The report needs to be followed with research funding so that the priorities highlighted can be researched for the benefit of resource-poor farmers.

If approved by NRI, sections of the report could be published as a refereed, scientific article.

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THE UNIVERSITY OF READING

Department of Soil Science

Review of Soil Fertility with regard to the Forest/Agriculture Interface System

NRI Consultancy

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Revised
March 1996

CONTENTS

EXECUTIVE SUMMARY

1 This report was commissioned by NRI to review the literature on soil fertility with regard to the forest/agriculture interface system.

2 The review demonstrates the complexity and diversity of the forest/agriculture interface. The interface includes a wide range of activities in which the relative proportions of crops and trees vary temporally and spatially and in which the level of external inputs varies considerably.

3 Many smallholder systems include no external inputs of nutrients so their ability to sustain agricultural production is dependent upon the inherent fertility of the soil, the ability of tree roots to "mine" deep nutrients and, depending on species, some biological nitrogen fixation. Because the predominant soils in the tropics are Oxisols and Ultisols with inherently poor fertility, crop production can be maintained for only short periods unless nutrients are added.

4 The review identifies 13 research needs in 3 broad areas of research: soil nutrients, roots, and soil organic matter. The 5 most important areas of research are as follows:

a) Sustaining crop production systems in the forest/agriculture interface through the judicious use of organic and inorganic inputs. The literature shows that the availability of organic materials is rarely sufficient to maintain crop production. Research is required to develop integrated systems of organic and inorganic fertilization.

b) The dynamics of P in tropical soils and the possible sources of P inputs into forest/agriculture systems is a priority for research. The literature demonstrates very clearly that organic sources of P are insufficient in many soils to sustain crop production for anything other than short periods.

c) The interactions of crop and tree roots require~~s~~ urgent investigation to determine the extent to which tree roots can tap deep sources of nutrients and effectively return them to crops. Knowledge of root morphology of trees and associated fungi will be necessary if closed cycling of nutrients is to be effectively promoted in forest/agriculture systems and to select appropriate species and provenances of trees.

d) The literature demonstrates the importance of organic matter in sustaining tree and crop production in forest/agriculture systems but most of the studies on organic matter transformations have been short-term. There is an urgent need for long-term studies of organic matter decomposition and of the release of mineralised nutrients.

e) The use of trees in "fallow" periods is worthy of further research to balance the previous research attention that has been paid to the spatial integration of trees into forest/agriculture systems. Research on the temporal distribution of trees will be advantageous in several systems.

1. INTRODUCTION

There is considerable scientific and development focus on the need to develop land management programmes in the tropics and sub-tropics to sustainably exploit the resources of these regions. A key element of these development strategies is the increase of food production. The two alternative approaches to increasing food production are; to increase the output per unit area farmed, or to increase the area farmed. Whilst both these strategies have been employed throughout the region for many years, the research focus has frequently been upon the former, with relatively little attention given to the potential problems and consequences of extending food production by developing new lands which increasingly may be marginally suited for agricultural production. This second option is frequently that chosen by the relatively poor land user, who may farm only a very small area. Whatever the option chosen, practices to increase the productive capacity of the tropics and sub-tropics must be both economically and environmentally sustainable, as the alternative is environmental, social and economic destruction.

A crucial area where expansion of the agriculturally exploited land is taking place is at the forest margins. This has resulted in the establishment of research and development strategies for this zone, described as the **'forest/agriculture interface'**. An important consideration in the development of these strategies is that frequently the soils within this zone are relatively stable and apparently productive when undisturbed, yet are often precariously fragile following conversion from forest to agricultural production. This has often resulted in wholesale destruction of lands in a very short time span after forest clearance. If these conversions are not to be wholly destructive it is essential that both the initial conversion and the subsequent management are based on sound scientific principles.

Whilst the 'interface' described above is perhaps the most straightforward, there are other contexts where trees and agriculture occur in close spatial association including, traditional shifting cultivation, the various agroforestry practices, and the many forest plantation activities. In addition there are situations where trees and agricultural activities occur at the same place but are separated temporally. This is also the case with most forms of shifting cultivation (although there are spatial interactions with the surrounding forest) and with a land management practice which has its antecedents in shifting cultivation, managed fallow systems. An important consideration in temporally mixed systems such as these is that there may be legacies, both beneficial and detrimental, from one system to the other, and these may have significant influences on the sustainability of the land use activities.

Where there is direct conversion of forest land to agricultural land it is frequently observed that the soils are exceedingly fragile once disturbed and without careful and appropriate management may be degraded to an extent where no crops may be grown and possibly the establishment of a secondary tree based vegetation severely impaired. It is essential that this disturbance alone does not result in the degradation of the soil system. Where land is cleared and agricultural production established, strategies must be developed to maintain and enhance the overall fertility of the system. The fertility in this context is defined as the provision of a satisfactory plant growing environment and will include both the provision of nutrients and the soil physical conditions to provide support, a satisfactory rooting environment and sufficient water. Fertility must also include a full recognition of the contribution of the soil biological system.

A key element of any successful development strategy for land at the forest/agriculture interface is that it must be based upon a sound understanding of the processes operating within the system. Only with such an understanding will it be possible to develop land use planning and management systems which provide a productive capacity which is both optimised and sustainable. Such systems will focus upon the sustainable management of both human and natural resources, and will acknowledge the need to integrate the components of these systems.

Systems involving trees and arable crops are composed of exceedingly complex and diverse subsystems. To develop sustainable strategies for land use planning and development these subsystems must be identified and fully understood, as must the interactions between the subsystems and their various components. Of particular importance in the forest/agriculture interface is the need to consider above and below ground interactions. These interactions are dynamic and the peak activity times within the various subsystems may occur at different times in the tree/crop growth cycle. Further, where perennial trees interface with annual crops it is essential that the relatively short and long term duration of the plants within the soil is fully recognised as this is likely to have a significant influence on the sustainability of any land use management system.

This review considers the nature of the behaviour of trees and crops in a range of management systems which might broadly be described as being at the forest/agriculture interface. In such systems a key element is the nature of the interactions between the tree components and the agricultural components. The development of sustainable management strategies must take full account of both the separate behaviour of the components and their interactions. Given that many of the current systems where agriculture and forestry occur in close association are developed on exceedingly fragile land there is often very little flexibility available to land managers. If the land use management system used is inappropriate, degradation and the loss of the soil's productive capacity may occur exceptionally rapidly, and attempts at remediation may be unsuccessful. Land use development and management systems for the forest/agriculture interface must recognise the potential fragility of the soil system and the need to maintain and enhance the soil fertility. This study seeks to review the existing understanding of a wide range of soil and soil fertility issues associated with the forest/agriculture interface and the potential development strategies available under a wide range of environmental conditions.

2. TROPICAL ENVIRONMENTS

2.1 Tropical climates

The geographical location of the tropics is generally accepted as being the area of land between the Tropics of Cancer and Capricorn, 23° 27° north and south of the equator;

an area covering 38% of the earth's land surface (5 billion hectares). This broad belt is the limit of the sun's apparent migration north and south of the zenith. Due to the continual high elevation of the sun, and the constant length of day, there is very little variation in mean annual seasonal temperatures (range 25° - 33°C).

A climate is thermally defined as tropical if the mean of the monthly temperatures is > 18°C (FAO, 1981), when corrected to sea level by subtracting 0.6° for a 100m drop in elevation.

The Tropics also receive half of the earth's rainfall, but there is great variation in its distribution. Water, and its availability, is undoubtedly the most important climatic factor affecting agriculture, and has therefore been used consistently as the main criterion to classify different tropical climates (Lal, 1987).

The rains can be unimodal, as in high rainfall areas close to the equator and low rainfall areas > 9° N & S, or bimodal, as in certain areas between latitudes 4° and 9° from the equator. The actual amount of annual rainfall varies. From > 4000 mm in the equatorial humid areas, to < 100 mm in desert areas of the higher latitudes.

Natural vegetation of the tropics is closely correlated with climate. It is widely accepted that there are 5 main vegetation types (Sanchez, 1976):

Table 2.1.

Vegetation type	Land area
Broad leaved evergreen 'rainforests'	30 % tropical land
Semi-deciduous and deciduous forests	15 % tropical land
Savannas and other grasslands	43 % tropical land
Desert shrubs and scattered grasses	7 % tropical land
Sparse to bare vegetation	5 % tropical land

On the basis of the above temperature, rainfall and vegetational differences the tropics are most often separated into 4 climatic zones, with characteristic rainfall and vegetation.

Table 2.2.

Climate	Rainfall	Vegetation	Area
Humid tropics (rainy climate)	1,500 - 4,000+ mm. bimodal / unimodal. 8.5-12 humid months.	Tropical rain forest. (Broad-leaved evergreen forest)	30%
Sub-humid tropics (seasonal climate)	500 - 1,500 mm unimodal / bimodal. 4.5-8.5 humid months.	Semi-deciduous / deciduous forest. Tall grass/low tree and Acacia/ tall grass savanna. (humid savanna)	52%
Semi-arid tropics (dry climate)	250 - 500 mm Unimodal 2-4.5 humid months.	Dry steppe, woodland, scrubland steppe. (dry savanna)	16%
Arid (desert climate)	0 - 250 mm unimodal. 0-2 humid months	Thorn and succulent scrub. (sparse or bare vegetation)	12%

(Source: Sanchez, 1976; Sprague, 1975; Landsberg *et al.*, 1963).

There is a further accepted tropical climatic zone, the Tropical highlands. Mountainous areas >900m in altitude, that cover approximately 23% of the tropics (Sanchez, 1976). Geographically and agriculturally this area is important, as it supports a considerable proportion of the tropical population. The highlands have lower annual average temperatures due to the elevation, but there is still little seasonal variation.

2.2 Tropical Soils

There is great variation in the physical, chemical and mineralogical characteristics of tropical soils, which relate to geological history, geomorphological characteristics and the intensity of soil forming factors (climate, organisms, topography, parent material and time) [Jenny, 1941]. There are at least five major soil classification systems for the tropics. Frequently misleading and inaccurate terminology can prevent meaningful comparisons and extrapolation of data between regions and classification systems (Sanchez, 1976).

This report will use the USDA Soil Taxonomy classification.

The major soils of the tropics are the Oxisols and Ultisols, that dominate the humid tropics (with greater relative importance in Latin America (82%) than Africa (56%) or Asia (38%)), Alfisols, which are found mainly in the sub-humid and semi-arid regions, and finally Aridisols, of arid areas. These, and the other soil orders of regional importance are described below:

Table 2.3. (Based on Juo, 1980)

Soil Orders of major importance within the Tropics

Alfisols:	Soils formed in well drained upland areas, of coarse to medium surface texture with a clayey B horizon, and a base saturation greater than 35 %.
Ultisols:	Similar to Alfisols, but more highly leached, with exchangeable bases of less than 35 %. They are found in the humid tropical and sub-tropical areas.
Oxisols:	Strongly weathered soils that exhibit very little variation with depth. Some of the strongly weathered red, deep, porous Oxisols contain large amounts of clay-sized iron and aluminium oxides.
Aridisols:	Soils of arid and desert areas, some of which are saline.

Soil Orders of relatively minor importance in the Tropics

Vertisols:	Dark clay soils containing large amounts of swelling clay minerals (smectite). When dry, wide deep cracks form. When wet they are sticky and difficult to work.
Mollisols:	Deep soils with well humified organic matter, often developed on colluvial materials. Soils are base rich with a high proportion of exchangeable calcium.
Entisols:	Soils exhibiting limited horizon development in the profile; mostly derived from alluvial and colluvial materials.
Inceptisol:	Young soils with incipient or limited profile development. They are mostly formed from colluvial and alluvial materials.
Histosols:	Soils very rich in organic matter such as peat and muck. Sometimes of major horticultural importance.
Andosols:	Soils developed on volcanic material, principally ash.

Soils of moderate to high fertility (Alfisols, Vertisols, Mollisols, Andisols, alluvial Entisols and high base status Inceptisols) cover 33% of humid tropical Asia, compared to 12% and 7% of tropical Africa and America, respectively. However, most of the fertile soils in Asia are already under cultivation, and 'problem' soils with severe management limitations are widespread (22%) [Sanchez *et al.*, 1989]. A major land use in the Asian Tropics includes the flooding of soils and Soil Taxonomy is only of limited use in the classification and characterisation of soils under these conditions.

For a basic understanding of how these soil types are distributed proportionately throughout the tropical climatic regions see the table below, (Sanchez, 1976).

Table 2.4. Soil groupings (Soil Orders) in relation to climate (M ha) as defined by number of humid months

Soil Groups	Rainy Climate (9.5-12)	Seasonal Climate (4.5-9.5)	Dry/Desert Climate (0-4.5)	Total M ha	% of Tropics
Highly weathered & leached (Oxisols, Ultisols and Alfisols)	920	1540	51	2,511	51
Dry sands and shallow soils (Entisols and lithic groups)	80	272	482	834	17
Light-coloured, base-rich soils (Aridisols and aridic groups)	0	103	582	685	14
Alluvial soils (Inceptisols and Entisols)	146	192	28	366	8
Dark-coloured, base-rich soils (Vertisols and Mollisols)	24	174	93	291	6
Moderately weathered & leached (Inceptisols and others)	5	122	70	207	4
Total area	1,175	2,403	1,316	4,896	100
Percentage of the Tropics	24	49	27	100	-

NB. > 9.5 humid months separates rainy from seasonal climates

2.3 Potential Tropical Arable Land

Various estimates for the limit of the total potential arable area in the tropics have been presented:

presented:	FAO (1969)	1145 M ha (total)
	President's comm.(1967)	1648 M ha (total)
	Norse (1979)	1666 M ha (total)

Precise evaluation of the potentially cultivable land area in the tropics is difficult because of the lack of baseline data on existing land use and land capability.
Norse (1979) estimates that globally just over 3 billion hectares of land is potentially cultivable. 53% (1666 M ha) of this area lies within the wet and dry tropics, but of this only about 30%, or 510 M ha is currently being cultivated.

Current observations suggest that the area of currently cultivated land increases all the time, and will continue to do so.

2.4 Deforestation

The estimated extent of tropical forests vary between different sources. Brown and Lugo (1982) estimate 1838 M ha whereas the World Resource Institute (1985) estimated 2346 M ha of tropical forest, woodland and forest fallow. A more recent estimate by FAO (1993) of the total tropical forest cover was 1756.3 M ha, a reduction from their 1980 estimate of 1910 M ha.

Another survey estimates that tropical forested areas and woodlands cover 2970 M ha comprising:

Table 2.5. Tropical forest types and areas

Forest type	Area (M ha)	Percentage
Broad leaved forest	1201	40
'Open' forest	734	25
Bush	624	20
Fallow in broadleaved forest	240	8
Open tree formations	170	6
Forest plantations	11	-
TOTAL	2970	100%

Source: Hadley and Lanley, 1983; Postel, 1984.

These various estimates include different tree formations under the umbrella of 'tropical forest' which makes comparison difficult, especially if the definitions are unclear.

Anderson and Spencer (1991) cite several estimates of the rate of forest clearance, that are based on the 1980 FAO UNEP Forest Resource Assessment. These range from 3 M ha yr^{-1} (Houghton et al., 1987), 6.9 M ha yr^{-1} (Lanly, 1982), up to 15.5 M ha yr^{-1} (Detweiler and Hall, 1988). Myers (1980a) gives an even more pessimistic estimate of 24.5 M ha yr^{-1}. The considerable variation in these estimates is explained in part by the different assumptions and definitions (Melillo, 1985). For example, Myers only rated deforestation of 'closed forest' at 7.5 M ha yr^{-1}, the rest of the 24.5 M ha yr^{-1} estimate was ascribed to 'disturbance' of forest fallow; something not included in the FAO/UNEP assessment.

The great variability in these estimates highlights a further problem. What is the exact definition of 'deforestation'? Barrow (1991) describes it is a much used, ill-defined and imprecise term and suggests limits can range from the marginal modification of cover (depletion), to fundamental transformation (degradation). The statistics seldom indicate the degree and definition (Myers, 1980b). This has important ramifications with regards to the forest agriculture interface where the importance of secondary forests (or forest fallows), generally formed following agricultural use (Brown and Lugo, 1990), has to be recognised.

An uncertainty when interpreting and comparing recent data in order to deduce rates of 'deforestation', in the extent to which improved measurement techniques reflect a real increase in the area being cleared (Park, 1992). The FAO estimated from 1981 - 85 data that the annual rate of deforestation was 11.3 M ha; following the 1990 assessment, this was increased to an annual deforestation rate of 15.4 M ha (FAO, 1993). This increase is considerable in global terms over a short period of time, but may simply reflect changes in methodology.

2.5 Causes of Deforestation. How much is for agricultural use?

The underlying causes of deforestation are extremely varied and the interrelationships complex. Population pressure has often been quoted as a major cause of forest clearance in the past. There is evidence that forest clearance results from population related demands such as fuelwood gathering (Foley, 1985; WWFN, 1988), progressive intensification and expansion of traditional (shifting cultivation) techniques and government resettlement schemes (Goldsmith and Hildyard, 1990; Economist, 1988). Two other important contributory factors are commercial timber logging (Caufield, 1985), and the conversion of forest land to pasture for extensive, low-intensity ranching (Economist, 1988). This final clearance activity is particularly important in Central and South America.

It is often difficult to judge how important one pressure is relative to another. With particular reference to this report one important question is how much of the forest clearance can be attributed to conversion from forest to agriculture. Myers (1984) has offered one estimate of the importance of different land use changes, but it is very generalised and omits certain recognised land use conversions.

Table 2.6. Estimated rates of clearance of tropical rainforests for different purposes.

Purpose	Annual Loss (km^2)	%
Commercial timber removal	45,000	18
Fuelwood gathering	25,000	10
Cattle grazing (S. America)	20,000	8
Farming operations (minimal estate)	160,000	64
TOTAL	250,000	100

(Myers, 1984)

Dominant causes of clearance in Asia are logging and agricultural expansion. In Africa logging has decreased as primary reserves are depleted and fuelwood gathering and overgrazing are now dominant. Latin America, the largest remaining forested area suffers from diverse clearance activities and although logging is limited, cattle ranching, population settlement schemes and development projects account for most clearance.(Park, 1992).

Whilst clearance has occurred for many reasons, clearance for agricultural use, chiefly by shifting cultivators, has been highlighted as the major cause (Steinlin, 1982). Shifting Cultivation, or 'Slash and Burn', in its various forms is a widely used traditional farming system in the tropics. It is the major form of farming activity for over 300 million people, on approximately 30% of the world's arable land (Andriesse and Schelaas, 1987). In its traditional form, in areas of very low population density, shifting cultivation is sustainable (Nortcliff, 1989; Janzen, 1973). It is when there is a reduction in the length of the fallow period, due to pressures of population, that forest degradation and progressive soil fertility decline occur. In addition, where mechanical clearance is undertaken there may be further problems of sustainability (Lal, 1986).

Precise estimates of the proportion of forest clearance ascribable to shifting cultivation are difficult. They include:
70% of rainforest loss in Africa
50% of Asian deforestation and
35% of Latin American deforestation
(Steinlin, 1982; Hadley and Lanley, 1983)

Globally, Postel (1984) estimated shifting cultivation was responsible for 50% of deforestation in the tropical rainforest zone. A recent attempt to differentiate between the degradation and depletion of forests by shifting cultivators estimates that annually 50,000 km^2 of tropical rainforest is destroyed, and a further 10 million km^2 are degraded annually (Goldsmith and Hildyard, 1990).

Tropical forestry, it is claimed, is going through the 'era of secondary vegetation' (Gomez-Pampo *et al*, 1974; Brown and Lugo, 1990). Most tropical countries have larger areas of secondary forest than primary (Brown and Lugo, 1990). As a result, secondary forests will be the major areas to be managed in the future (Ewel, 1979). Globally, secondary forests occupy 31% of total closed tropical forest, and 19% of tropical open forest (Lanly, 1982). Whether this area of secondary forest is derived from agricultural land, logging activity or another land use varies with country and continent. (Lanly, 1982):

47% of secondary forest formation in Asia occurs from logging.
46% of secondary forest formation occurs from agriculture in tropical South America.

Furthermore, an important conversion trend from forest - logging - agricultural land use is evident in certain areas. For example, 72 - 76 % of the agricultural/forest fallow land in Asia and Africa originated from previously logged land whereas in Tropical America, 58% of secondary forest originates from previously undisturbed forest (Lanly, 1982; Brown and Lugo, 1990).
This, along with gradual mechanisation of the land clearing practice, has considerable ramifications for the status of soils that become cultivated.

3. NUTRIENT CYCLING

3.1 Forest Clearance and Change in Soil Fertility

It has long been recognised that a quantitative understanding of the nutrient pools, and the processes that connect them with the rest of the system could lead to more efficient and sustained management of agricultural systems (Nye and Greenland, 1960; Swift, 1987).

3.2 Natural tropical forest systems

Tropical forests thrive on both fertile and infertile soils. However, over half of all tropical soils are highly weathered (Sanchez, 1976) and the majority of tropical forests are found on such soils. Why are such soils so productive?

Productivity, the rate at which biomass is synthesised, is an important ecological parameter.
If productivity in a natural system changes little over a long period of time, it suggests that either the environment is unchanging or that organisms or populations are compensating for changes which are occurring (Jordan, 1985). Many factors can limit productivity in natural ecosystems. For tropical forests it has been believed for many years that nutrients may often be limiting (Richards, 1952). The means by which tropical forests can support such high biomass or productive stands is through efficient nutrient cycling. Until recently this theory was based on purely circumstantial evidence (Proctor, 1983).

The total amount of nutrient accumulated in the biomass of a given forest ecosystem depends on the inherent fertility of the soil (Furch and Klinge, 1989). Forests growing on less fertile soils are less productive and as a result recycle smaller amounts of nutrients (Table 3.1.).

Table 3.1. Leaf litter fall (t ha^{-1} yr^{-1}) and amount (g m^{-2} yr^{-1}) of nutrient elements from Varzea and Igapo primary forests near Manaus, Brazil (Furch and Klinge, 1989)

Forest	Soil	Litter fall	N	P	K	Ca	Mg
Varzea	loamy alluvial deposits	10.6	15.5	1.0	7.2	31.4	6.1
Igapo	leached sand on kaolinitic clay	5.0	8.0	0.1	1.5	2.8	0.7

Carbon and nutrients in all tropical forest systems are transferred to the soil by litterfall, root senescence and exudation. Litterfall additions range from 10.6 t ha^{-1} yr^{-1} to 5 t ha^{-1} yr^{-1} (Furch and Klinge, 1989; Vitousek and Sandford, 1986). As yet, there are few substantiated estimates of below ground inputs. The maximum value suggested is 16 t ha^{-1} yr^{1} (Vitousek and Sandford, 1986).

The dead organic matter on the forest floor can contribute 50% or more of the total carbon pool (Brown and Lugo, 1984; Vogt *et al.*, 1986) including intact litter (> 2 mm) and soil organic matter. However, the forest type must be qualified, as certain primary forests can contribute up to two thirds of C as plant biomass (Woomer *et al.*, 1994).

3.3 Organic Matter

The organic inputs decay and are converted into available nutrients and soil organic matter through decomposition by soil fauna / and microflora activity. The amount and composition of the soil organic matter (SOM) are important as it is forms the major soil storage pool for nitrogen and sulphur, and is an important store for phosphorus, calcium, potassium and magnesium, as well as other micronutrients (Jordan, 1985). In frequently weathered and acid, tropical soils with kaolinitic clays of variable charge, SOM is further critical for ion retention and soil aggregation (Duxbury *et al.*, 1989; Oades *et al.*, 1989).

10 - 20 % of the aboveground litter and 50 % of root litter may be converted to humus (Nye and Greenland, 1960), and the rest is mineralised as CO_2. This resultant soil organic matter can be differentiated into 3 dynamic pools:

a) an active (light) fraction of cellular material dominated by the microbial mass.
b) a slow fraction.
c) a passive fraction of non cellular, recalcitrant, humified material.

The slow and passive fractions have estimated turnover times of 5 and 150 years respectively (Parton *et al.*, 1987). These 'heavier' fractions can undergo biochemical stabilisation, complexing with clays and other minerals so that clay soils (especially Andisols) often have higher organic matter contents (Buringh, 1984; Sanchez et al., 1982). Oxidic and allophanic minerals stabilise C but the relationship between mineralogy and C stabilisation is not a simple one because pH and the total clay content appear to influence the amount of C stabilised (Motavalli *et al.*, 1994).

The active fraction of SOM is of particular interest in tropical forests, as its contribution to nutrient supply is disproportionate to its size. With a turnover rate between months to a year, depending on chemical composition (Anderson and Swift, 1983), the active microbial fraction can respond very rapidly to changes in management practice (Paul and Juma, 1981).

High rates of biological activity, combined with constantly high temperatures and frequently high humidity (humid forests) results in a large potential for nutrient loss via leaching. Efficient cycling is thus dependent on a variety of integrated biological components and processes in the soil-plant system (Palm *et al.*, 1995). Mechanisms and adaptations naturally occur in tropical forests to efficiently capture and conserve nutrients (Proctor, 1989; Jordan, 1985) and include:

1. A large root biomass - concentrated near the soil surface forming a relatively thick root mat intimately mixed with the litter and decomposer fraction. This reduces nutrient transfer distances and can be very effective in recycling and preventing loss (Stark and Jordan, 1978).

2. Mycorrhizal associations - enhance uptake abilities through an increased surface area and in the case of phosphorus, through solubilisation of otherwise unavailable forms. A theory of 'direct' cycling from decomposing litter via mycorrhizae (amongst other pathways) has been suggested from recent evidence (Janos, 1983; St. John and Coleman, 1983).

3. Surface / below ground community of micro / macro organisms - form a complex succession series of smaller cycles that are different in detail in almost every case (Swift *et al.*, 1979). The successional community acts as a nutrient conserving

community as long as the elements are bound in some way. Destruction of this below ground community destroys an important part of the tropical forest's nutrient retaining capability (Jordan, 1985).

It is argued that there is a dynamic, competitive interplay between tropical tree roots and the decomposer community for the nutrients that the decomposers release. Overt competitive success by the trees is self-defeating because the decomposer community dies back, thereby starving the soil of nutrients so that the trees die back creating forest gaps for regeneration (Hartshorn, 1978; Jordan, 1985). Such sensitivity within tropical forest-soil environments highlights the difficulties inherent in successful clearance and subsequent soil management.

It has been postulated that tropical forests retain the majority of nutrients in the forest biomass as a further conservation mechanism preventing losses (Anderson and Spencer, 1991). The forest floor encompassing litter, roots and soil can often contain at least 50%, and as much as 80% of the N and P in the tropical forest system, (see Table3.2).

Table 3.2. Carbon and nutrient pools and fluxes for tropical lowland forests (mean values).

POOLS

	SOM t ha^{-1}	N (kg ha^{-1})	**P** (kg ha^{-1})	K (kg ha^{-1})	**Ca** (kg ha^{-1})	**Mg** (kg ha^{-1})
Above-ground	344	1334	107	955	1801	288
Litter	37	403	11.6	26	180	28
Roots	41	442	12.3	96	561	49
Soil	230	4581	406	249	3579	425
% in forest floor	**47**	**80**	**80**	**28**	**68**	**64**
FLUXES						
Rainfall:input		15	10.9	11.6	13.9	3.6
Enrichment		32.5	2.7	113.6	25.9	20.9
Litterfall	9.3	149	7.3	64.6	137	32
Streamwater losses		30	0.7	11.8	63.3	32

(Source: Anderson and Spencer, 1991 from Proctor, 1987; Vogt *et al.*, 1986; Anderson and Swift, 1983).

The cycles of all nutrient elements can be classified into two very different types;

volatile and non-volatile (Deevey, 1970). In volatile cycles, nutrient elements pass through a gaseous phase. Important examples are N and S, as well as the building blocks of organic matter, C, H & O.

3.4 Nutrient cycles

Nitrogen inputs to a tropical forest ecosystem occur via:

a) Biological nitrogen fixation is the primary input, reducing atmospheric N to ammonium(NH_4) (Delwiche, 1977). This is performed by N-fixing blue/green algae in symbiotic relationships with fungi, liverworts, ferns, some trees and in free-living forms on leaves and in soil (Forman, 1975; Stewart, 1977). Measurements indicate that the contribution of fixation is considerable in tropical rainforests becasue the continual wet and warm climate of the humid tropics allows very high annual fixation, >35 kg N ha^{-1} (Jordan *et al.*, 1982).

b) Dry and wet deposition are normally insignificant but following burning (common practice in shifting cultivation), this form of N input can be high (Lewis, 1981; Jordan, 1985).

Once fixed, N begins a cycle within the ecosystem in which it is taken up and then incorporated into amino acids and plant proteins. Nitrogen's next major transformation occurs when it is returned to the soil during organic matter breakdown from complex nitrogenous compounds to simpler forms (Delwiche, 1977). Some nitrogen, along with S and P, is mineralised quite rapidly in weeks or months. Temperature, moisture, the carbon to nitrogen ratio (C / N), and lignin content influence the rate of decomposition by micro-organisms (Swift *et al.*, 1979). A low C / N ratio (< 25 / 1) indicates high nitrogen content and a favourable environment for bacterial activity (Jordan, 1985).

Nitrogen is rarely limiting in natural tropical forests. It is found in comparable amounts to natural temperate ecosystems, is stored mainly in the undecomposed organic matter (Brady, 1974), and is not leached readily (Vitousek and Sandford, 1986; Medina and Cuevas, 1989; Heaney and Proctor, 1989). Nitrogen limitation may occur in dry regions as a result of a lag between root growth and N availability as microbial biomass responds more slowly to favourable conditions.

In contrast, elements such as Ca and K are adsorbed on surfaces of clay-humus colloids and are thus are open to replacement by H and Al ions. Phosphorus is more frequently the limiting nutrient in natural tropical forests, for the following reasons:

> a) The rate of P input from the atmosphere (see Table C.2) is low compared to other major nutrient elements, making soil P all the more important. Most P is derived from the chemical breakdown or weathering of parent material.
>
> b) Phosphate is adsorbed by sesquioxides and clays of Oxisols and Ultisols (Uehera and Gillman, 1981), and by allophane in otherwise fertile volcanic soils (Fassbender, 1969; Vitousek and Sandford, 1986). Most organic phosphorus is not covalently bonded directly to C but rather is held by ester linkages that can be cleaved by extracellular phosphatases (McGill and Cole, 1981) and so can cycle independent of SOM decomposition.

Weathering is intense in most tropical soils, especially highly acid Oxisols and Ultisols, as soil pH governs phosphate reactions with Fe, Al and Mn, forming insoluble hydroxy phosphates (Brady, 1974). This pH relationship is mirrored in calcareous soils where pH is high and as a result Ca reacts with soluble P compounds rendering P insoluble (Brady, 1974). In-between, there is an optimum for soluble P forms.

Despite the large proportion of insoluble P, uptake in natural tropical forests is sufficient to sustain productivity. This is facilitated through the action of soil micro-organisms producing organic acids. These acids chelate Fe, Al and Mn and play a key role in P availability (Graustein *et al.*, 1977). Mycorrhizae may also be crucial through direct uptake (Herrera *et al.*, 1978a; Jordan, 1985), or via oxalic acid production mobilising recalcitrant organic phosphorus (Sollins *et al.*, 1981; Jordan, 1985). P mobilisation relies on soil micro-organisms in undisturbed tropical forests and conversion to agriculture frequently leads to P scarcity as these mechanisms for mobilisation are lost (Olson and Engelstad, 1972).

Potassium and Mg are conserved through plant biomass retention in acid soils with low cation exchange capacities (see Table C.2).

Although the details of nutrient cycles differ at an elemental level, two different nutrient cycling mechanisms are recognised at an ecosystem level for primary forests in the tropics:

1. Internal cycling (closed) simply involves cycling nutrients from decomposing litter to recapture by the root mat on the forest floor. Primary forests established on strongly leached and acid soils weathered to in >2-3 m rely on internal cycling to meet their mineral requirements. Examples are old Oxisols and Ultisols in areas of high rainfall such as the Amazon and Congo Basin rainforests. Base cation concentrations are low in surface horizons, and over 80% of N and P are held by the forest plant biomass (Scott, 1978; Jordan, 1985), whereas the majority of K, Ca and Mg are located in the soil (Sanchez ,1976). (It should be noted that these results from South American studies contradict the general patterns shown in Table 3.2.). Atmospheric inputs are important in such situations and may represent 7 - 11% of the litterfall nutrient inputs (see Table 3.2).

2. External cycling (open) involves cycling of minerals from the subsoils in addition to the internal cycling (Jordan *et al.*, 1972; Herrera *et al.*, 1978b; Palm *et al.*, 1995; Baillie, 1989). For primary forests situated on soils of high base status, availability of mineral cations is closely related to parent rock composition. Correlation between 'reserve' quantities of K, Ca and Mg elements and the vegetation composition has been shown in dipterocarp forests (Baillie and Ashton, 1983). Weathering occurs in the root zone and elements weathered in excess of plant demand are leached to groundwater. Subsequently, K, Ca, and Mg losses often exceed precipitation inputs on fertile soils such as young Inceptisols and Entisols. The Alfisols and Andisols of Central America and West Africa similarly benefit from 'open' cycling as do extensive areas of forest in Malaysia, Indonesia and New Guinea found over shallow, non-cation limiting, soils (Lamb, 1980; Burnham, 1989; Bruijnzeel, 1989).

It is important to differentiate between the productivity of primary forest systems which are sustained by weathering of parent material in open cycles and the productivity of closed cycles with nutrients accumulated over centuries where weathered products are inaccessible to forest roots. Important that is, for an understanding of the impact large or small scale disturbance will have on subsequent nutrient cycles (Baillie, 1989; Burnham, 1989).

4. NUTRIENT CYCLING AND SOIL ORGANIC MATTER DYNAMICS IN MANAGED SYSTEMS

4.1 Fertility Change During Shifting Cultivation

Shifting cultivation in its traditional form is a disturbance of moderate intensity, normally at a small scale and of a short duration (Jordan, 1985). The structure of the forest is destroyed, but the soil is not degraded to the point where native vegetation cannot re-establish. There are many variations of shifting cultivation that reflect diverse, local conditions. Despite this there are common patterns of nutrient cycling and productivity, most notably described by Nye and Greenland (1960).

4.2 Slash and Burn

Firstly, the site is felled manually, a process that can take 60 to 180 man-days ha^{-1} depending on whether the clearance is incomplete or complete (Couper *et al.*, 1981). Partial clearance followed by flash burning is recognised as the traditional practice, nutrients are then released both by the burn and later by decomposition (Andriesse and Schelaas, 1987).

1. Slash mulching

The cut trees and shrubs are allowed to dry for several weeks to months before burning. This mulching period may include considerable nutrient loss. Ewel *et al.* (1981) noted a loss of 35 % K and 13% P from the slash over an 11 week mulching period. A corresponding increase in topsoil K and P occurred, but accounted for less than half of that originally lost.

Mackensen *et al.* (1995) studied the export of macro-elements from Eastern Amazonian slash and burn sites during slash mulching and the burn itself. Of 3 sites they found the 2 surrounded by high forest stands lost significant amounts of K, Na and P from the debris through leaching, prior to the burn. These do not necessarily leave the rooting zone.

Harvesting of trees is also recorded during the clearance stage, increasingly becoming common practice due to greater general accessibility. Harvesting during Ewel *et al.*'s (1981) observations removed 18% S and more than 10% of every other element (except N) from the biomass store.

2. Burning

Burning is almost universally practised in shifting cultivation, where climate permits. Nutrients are released, but are either deposited in ash or are volatilised. The magnitude of soil and air temperature during burning depends on the quality and quantity of fuel available (Lal, 1986). Temperatures can reach 650°C at 2 cm above the surface and soil surface temperatures are commonly about 200°C (Ewel *et al.*, 1981, Zinke *et al.*, 1978). In excess of 1100°C has been recorded from a woody fuel flame in windy conditions (Raison *et al.*, 1985). Temperatures high enough to sterilise the soil (75°C) have been recorded down to 5 cm depth (Lal and Cummings, 1979).

3. Nutrient Dynamics in the slash and burn process

N has the lowest volatilisation temperature at 200°C, and the relationship between percentage N loss and the mass loss of fuel is close to 1:1. As a result, accurate predictions of N loss can be made with a knowledge of N content of the fuel and degree of combustion (Raison *et al.*, 1985). For example, Mackensen *et al.* (1995) found N losses during debris burn of 95 - 98% of the N stock in the debris corresponding to the amount of fuel reduction (91 - 96%). These and losses of other elements are shown in Table 4.1. As Ca losses are mainly through particle transport, the greater %Ca loss from site 3 may be due to higher windspeeds.

Table 4.1. Nutrient transfer from the ecosystem to the atmosphere by burning. Absolute values (kg ha^{-1}) and relative values (%) referring to the stock in the burnt debris.

	N	S	P	Na	K	Ca	Mg
Site 1. kg ha^{-1}	325	26	2	3	12	28	6
%	95	67	27	23	16	9	17
Site 2. kg ha^{-1}	817	72	8	8	84	188	41
%	98	68	33	17	31	25	44
Site 3. kg ha^{-1}	199	34	4	6	35	102	17
%	96	76	47	30	48	35	40

Such large nutrient losses to the atmosphere cannot be replaced through atmospheric deposition during the subsequent land use. This brings into question the sustainability of slash burning (Mackensen *et al.*, 1995).

Volatile elements generally suffer more severe loss during burning. For example, 30 % C, 22% N and 49% S losses from slash to the atmosphere have been reported in Costa Rica, by Ewel et al.(1981). In this study other non-volatile elements showed no detectable losses and were assumed to have been transferred to the soil and ash residue pool.

P losses are often thought to be minimal during burning. However, the fine grey/white ash often has a P concentration 50 times that of the unburned fuel (Raison *et al.*, 1985) and is easily transported in smoke columns, or subsequently by wind or water action, resulting in a substantial potential export which is most likely to be permanent (Raison *et al.*, 1985; Toky and Ramakrishnan, 1981). Ewel *et al.* (1981) noticed the importance of this post-burn, wind blow, erosion and leaching, reporting 40 - 51 % of pre-burn forest Ca, Mg and P was lost through such processes. It is recognised that if the period of rotations is shortened, N losses through burning slash, volatilisation and windblown fine ash can lead to progressively impoverished soil pools (Scott, 1986; Ramakrishnan, 1989).

4. Nutrient input from ash

The amount of mineral elements released through burning depends upon the total nutrient content in the biomass and the intensity of the burn. The total amount varies from one site to another, but the general trend is Ca > K > Mg > P (see table 4.2

from Juo and Manu, 1995). The ash often has a very high concentration of K, as most K prior to burning, is stored in the above ground biomass pre-burn (Nye and Greenland, 1960; Brinkman and Nascimento, 1973). Stromgaard (1984) reported an immediate increase in soil K, even at 40 cm depth, which he ascribed to a heat effect.

Table 4.2. Estimated nutrient inputs (kg ha^{-1}) from ash at 3 locations.

Location	N	P	K	Ca	Mg
Sri Lanka	3	10	76	730	66
Yurimaguas, Peru	67	6	76	75	16
Nam Phrom, Thailand	54	72	455	3373	288

(Sources: Juo and Manu, 1995, citing Sanchez, 1976; Kyuma *et al.*, 1985; Andriesse and Schelaas, 1987)

5. Effect of burning on soil chemical properties

The magnitude of the changes in soil chemical characteristics following land clearing and burning are influenced by both the chemical composition of the ash and the capacity of the soil to retain and store those nutrients. The latter is determined by the mineralogy and charge characteristics of the soil, and the rainfall regime (Kang and Juo, 1986; Juo and Manu, 1995). The main changes in soil properties are:

a) pH - Following burning an increase in soil surface pH is consistently found (Table 4.3) as a result of alkali and alkaline cations (Na, K, Ca & Mg) being released from the ash (Seubert *et al.*, 1977; Kang and Juo, 1986).

Table 4.3. Changes in pH (water), available P (mg/kg), and exchangeable bases (cmol$_c$ kg $^{-1}$) in the surface soil following clearing and burning of forest fallow. (Juo and Manu, 1995, citing Nye and Greenland 1960; Kyuma *et al.*, 1985; Sanchez *et al.*, 1983; Kang and Juo, 1986.)

Location	**Soil Group**		**pH**	**P**	**Ca**	**Mg**	**K**
Nam Phrom, Thailand.		Before burn	6.2	1.4	17.0	5.6	0.45
		After burn	7.2	7.7	36.3	7.5	1.93
Kade, Ghana.		Before burn	5.2	9.8	5.7	1.2	0.41
		After burn	7.9	30.0	17.9	2.7	2.01
Yurimaguas, Peru.		Before burn	4.0	12.0	1.0	0.3	0.25
		After burn	4.7	23.7	2.3	0.6	0.39
Onne, Nigeria.		Before burn	4.3	-	1.3	0.3	0.16
		After burn	5.0	-	3.0	0.9	0.33
Ibadan, Nigeria.		Before burn	6.0	4.7	5.9	1.6	0.33
		After burn	6.3	20.7	7.5	1.9	0.97

b) CEC - The increase in pH also increases the effective cation exchange capacity (CEC), especially in soils containing predominantly variable charge clay minerals (oxides and kaolinite). Initially the CEC may decline, possibly as a result of Ca and Mg alterations at depth (Stromgaard, 1984), but soon recovers and surpasses the previous CEC. Romanya *et al.* (1994) reporting results of clearfelling and slash and burning of Eucalyptus forest on yellow, podzolic, duplex soils in Australia, noted that total and inorganic P increased after burning, the increase being dependent on the intensity of the burn. Fire also increased the sorption capacity of the ashed soil, but P was less tightly bound than in unburnt soils. The increase in P sorption capacity exceeded the actual ash P input, therefore losses from leaching are unlikely.

c) Al - The ash also significantly alters the amounts of soluble and exchangeable Al in the soil (Kang and Juo, 1986), a feature of considerable impact in acidic soils (Oxisols and Ultisols) with beneficial effects for the crop-soil environment (Nye and Greenland, 1960; Stromgaard, 1984; Tulkaphitak *et al.*, 1985). Where P is limiting (common in the wet tropics), as Al and Fe become more soluble, phosphate that was previously complexed at low pH also becomes soluble and plant available (Jordan, 1985).

The effects of increased availability of P, Ca, Mg and K, decreased soil acidity and aluminium saturation due to ash inputs are reversed with time. Such a reversal occurs considerably earlier in coarse textured soils than in clays (Sanchez *et al.*, 1985). Decomposing forest residues produce organic acids that can also counteract the effects of the ash in time (Anderson and Spencer, 1991).

During the cultivation phase following burning, a substantial amount of the soluble and available P released from ash and mineralised organic matter may be fixed by oxides in the soil. Clearance, burning and cultivation may partially or completely destroy mycorrhizal root associations and other soil micro-organism communities, and thereby reduce the immobilisation of P. As a consequence, P can become the first limiting nutrient for biomass production, especially in strongly weathered soil during cropping and the subsequent fallow cycle (Jordan, 1985; Szott *et al.*, 1991).

4.3 Soil Organic Matter

Soil organic matter (SOM) is crucial to the productivity of the cropping phase of slash and burn, as it helps maintain soil fertility by storing organic and mineral forms of nutrients, and helps maintain soil structure (Palm *et al.*, 1995).

1. <u>Inputs from the cropping phase</u>

Following slash and burn the major component of organic inputs consist primarily of dead roots from the cut and burned vegetation. Up to 60 % of the above ground biomass may be burnt (Palm *et al.*, 1986), the rest decomposes either on or off the site, dependent on management practice and climatic conditions (Andriesse and Schelaas, 1987; Jordan, 1985). Total root mass varies between 10-130 t ha^{-1}. (Jordan *et al.*, 1983). Hendrikson and Robinson (1984) suggest that on average there is 50 t ha^{-1} below ground root mass which provides a source of nutrients on decomposition.

Fresh inputs during the cropping phase are restricted to crop roots and crop residues. Such organic inputs represent only 30 - 40 % of the tropical forest system inputs (Sanchez and Benites, 1987) and many systems simply do not recycle the available residues. It has been estimated for humid forest soils that 8.4 t/ha/yr of above ground biomass and 5.8 t/ha/yr of below ground inputs would be necessary to maintain SOM levels (Young, 1989a). Timing, chemical composition and placement of these inputs as well as the amount are important (Sanchez *et al.*, 1989) as this will influence decomposition, nutrient availability and use-efficiency as well as the resultant SOM content and composition (Palm *et àl.*, 1995).

2. Decomposition

Organic inputs are converted into available nutrients and SOM through decomposition controlled by the physiochemical environment which includes climate and soils, resource quality and the type of decomposer community (Swift *et al.*, 1979). The relative importance of the above factors varies and changes over time in all systems (Palm *et al.*, 1995).

It is thought that decomposition rates increase after clearing as a result of microclimate change, particularly an increase in soil surface temperature. Higher insolation is received at the soil surface which increases soil temperatures by as much as 5°C at 10 cm below the surface and 2-3°C at a depth of 30 cm compared to adjacent forested soils (Tulaphitak *et al.*, 1983; Lal, 1986). However, a reduced rate of decomposition (10 - 18%) has been recorded for fresh leaves on a cleared soil surface (Ewel, 1976) attributed to extreme temperatures drying the litter and temporarily inhibiting decomposition. Burying the litter in the cleared soil resulted in the expected increase in decomposition rate compared to buried litter in forest soil (Santos and Grisi, 1979; Palm *et al.*, 1995) as desiccation was eliminated.

3. Decomposer community

The microclimate also affects the decomposer community and macrofaunal biomass can fall by up to 70 % after just one year's cropping (Lavelle and Pashnasi, 1989). A lack of vegetational cover is suspected as the causal factor. The burn itself can cause a 53 % decrease in macrofaunal biomass recorded after a slash burn in Thailand In addition the fungal biomass did not recover to pre-burn levels during the two years of cultivation (Watanabe and Ruaysoongnern, 1984; Palm *et al.*, 1995). Microflora show rapid and drastic changes in the top soil as a result of fire effects, low soil moisture and pH change (Cerri *et al.*, 1985; Palm *et al.*, 1995) but invariably recover to pre-burn levels within months (Deka and Mishra, 1983).

Burning, extreme soil moisture and temperature, lack of food resources and soil compaction are all believed to contribute to faunal biomass reduction (Critchley *et al.*, 1979) but as yet there has been no research into the relationships between decomposition rate and faunal changes (Palm *et al.*, 1995).

4. Mineralisation and Nitrification

Mineralisation of SOM is controlled by the same factors as decomposition:

a. the physiochemical environment;
b. the composition of SOM; and
c. the total soil biota.

Initially, with clearing and burning there are increases in mineralisation rates, followed by a reduction (Mueller-Harvey *et al.*, 1985). Matson *et al.* (1987) measured N mineralisation, nitrification rates and total NH_4 / NO_3 levels following burning. Mineralisation increased by 45% in surface soil during the 6 months following burning, then returned to background levels similar to those of a secondary forest soil. Estimates of C mineralisation by measurements of soil respiration showed an increase up to 17.1 t ha^{-1} after the first year, from 11.7 t ha^{-1} pre-burn (Tulaphitak *et al.*. 1985). Again, the majority of the increase occurred early during the first eight months. There was virtually no difference between soil respiration in the cleared and cultivated soil, and the forest soil in the second year.

The general pattern of rapid increase, then gradual return to base level rates of mineralisation may be due to factors of varying combination and importance, making trends difficult to predict :

a - A labile 'active' fraction of SOM is readily decomposed leaving the more resistant slow and passive forms (Hendrikson and Robinson, 1984).
b - The labile 'active' fraction of SOM is not replenished because of a reduction of organic inputs following clearing (Sanchez *et al.*, 1989).
c - A reduction in soil fauna. (Lavelle and Pashanasi, 1989).
d - Changes in the soil physio-chemical environment, including moisture, temperature, soil pH and nutrient status.

(taken from Palm *et al.*, 1995)

Nitrification often increases following the cutting of forests (Robertson, 1989; Uhl and Jordan, 1984) but returns to pre-burn levels later (Matson *et al.*, 1987). This increase could be as a result of removal of nitrification inhibition. Montagnini and Buschbacher (1989) found nitrification rates to follow closely total N mineralisation rates and it was ammonium availability that appeared to regulate nitrification at both undisturbed and slash and burn sites. Nitrification produces protons (H^+) and in soils dominated by variable charge clays these can reduce the CEC whilst enhancing the anion exchange capacity (AEC) so that nitrate rather than ammonium and base cations are retained by the exchange complex (Robertson, 1989). The large pool of nitrate is balanced by a correspondingly high concentration of nutrient cations in soil solution and will thus be open to leaching loss (Toky and Ramakrishnan, 1983).

5. SOM. dynamics during cultivation

Studies on SOM change following conversion of tropical forest to agriculture are many and varied (see for example Schlesinger, 1977, 1984; Buringh, 1984; Allen, 1985). There can be as much as a 20 - 60% loss of C from the top 30 cm when forested land is cultivated (Young, 1976; Schlesinger, 1984).

For conversion of forest to shifting cultivation, a synthesis of studies by Detweiler (1986) indicates a decrease of 17 - 27% SOM in the top 40 cm during the cropping phase of shifting cultivation. Whether crop residues are returned is of considerable consequence. SOM losses can be reduced from 30% to only 10% following 2 years maize cropping if the residues are returned (Ayanaba *et al.*, 1976).

It has been postulated that the time course of SOM decomposition following forest clearance and cultivation gives an indication of the proportion of the active, slow and passive SOM fractions discussed previously (Hendrikson and Robinson, 1984). Brams (1971) looking at organic matter content on Ferralitic and Alluvial tropical soils, found similar decomposition rates over time. The initial rapid decline in soil C represents the rapid decomposition of the active fraction and fine roots. The [?] rate decreases again reflecting carbon losses now occurring in the slow fraction. Finally the rate levels off as residual carbon remains only in the passive SOM fraction.

The amount of C lost over time varies considerably. Harcombe (1977) reported a loss of 7 - 54% over one to three years of shifting cultivation cropping for seven different disturbed forest soils. Allen (1985) also showed major differences in organic C losses (Figure 4.1) from a range of soil orders after forest clearing under a range of management systems (shifting cultivation, pasture and plantation).

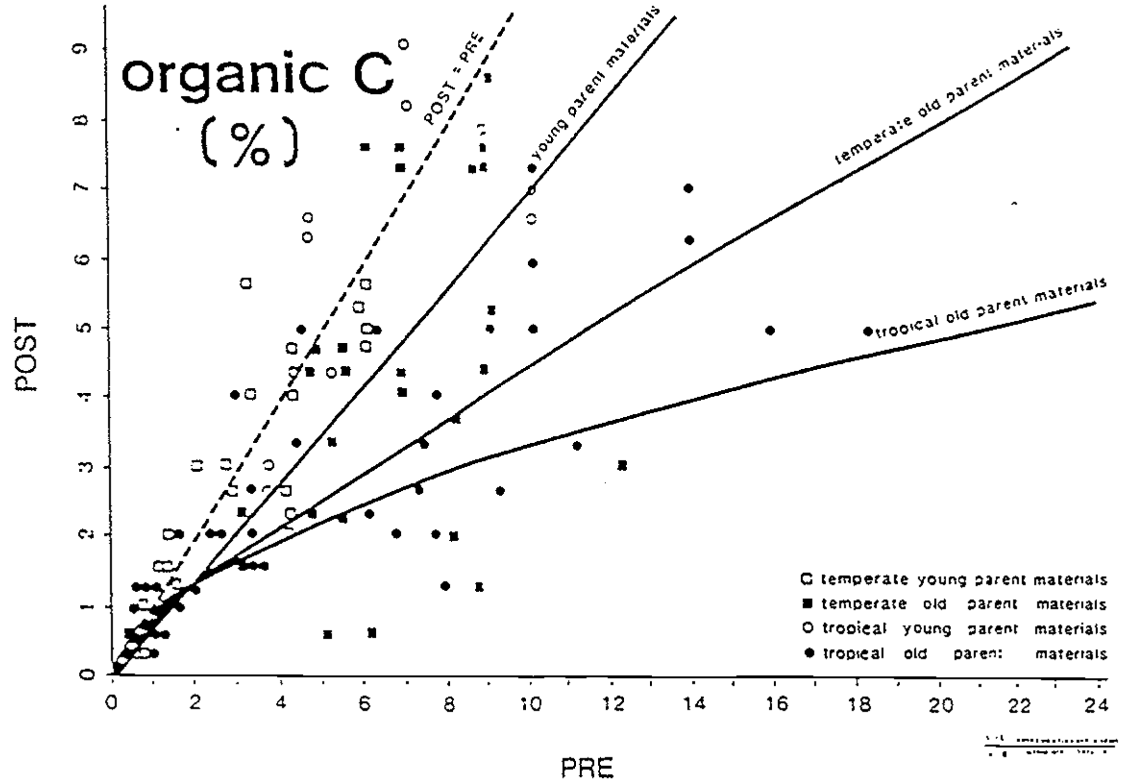


Fig. 4.1 Estimated losses of organic C associated with deforestation in soils developed on old parent materials in the tropics and all other climate/parent material groupings. $Y = -.156 + .927^{***}X - .214D_1 - .051(D_1X) - .194D_2 + .128(D_2X) + .594^{**}(D_1D_2) - .431^{***}(D_1D_2X)$; $(R^2 = .90)$, where X, Y = natural log of preclearing and postclearing organic carbon respectively, D_1, D_2 = group variables for soil parent material and climate respectively, *** indicates significance at the .001 level, and ** indicates significance at the .01 level. Regression based on 205 weighted observations of organic carbon in 0–30 cm depth of soil before and after natural forest clearing (Allen 1983, Brams 1971, Byrnes and Kardos 1963, Cunningham 1963, Dils 1953, Dyrness and Youngberg 1957, Ewel *et al.* 1981, Gerakis and Tsangarakis 1970, Gilmore and Boggess 1963, Hecht 1982, Jenny *et al.* 1949, Knighton 1977, B. Lundgren and L. Lundgren 1972, B. Lundgren 1978, L. Lundgren 1980, Nye and Greenland 1964, Rolfe and Boggess 1973, Sartz 1973, S. J. Smith and Young 1975, Tiedemann and Klemmedson 1973, Watson 1977, Wooldridge 1964, Youngberg 1959).

The analysis concluded that absolute losses were greater in soils on young, less weathered parent material, although relative losses were 50% greater in soils on more highly weathered parent material. This suggests greater resilience of SOM in Andisols (Harcombe, 1977), Mollisols and Inceptisols, compared to Oxisols and Ultisols under the same tropical climatic conditions (Werner, 1984). There is extreme variability in all soil carbon loss or SOM loss investigations, and predictive understanding must take into account the soil type, climate and management practice following clearance (Palm *et al.*, 1995).

6. <u>S.O.M. fractions and soil fertility</u>
A measurement of a change in total SOM does not necessarily correlate with a change in soil fertility (Nye and Greenland, 1960). The soil microbial mass correlates well with available nitrogen (Myrold, 1987; Bonde *et al.*, 1988) and therefore a measurement of the directional change in the soil microbial mass 'active fraction'(Powlson *et al.*, 1987), or the ratio of soil biomass C to total soil C (SMC/TC), may serve better as an early indication of long term change in total SOM or sustainability (Sparling, 1992; Swift and Woomer, 1993). The research by Ayanaba *et al.* (1976) discussed previously, included microbial C measurement and showed a 27% decline over 2 years, accompanied by only a 10% decline in total C. The relative size of the passive SOM pool may mask the dynamics of the active fraction relevant to soil fertility (Bonde *et al.*, 1988; Bonde, 1991).

4.4 Nutrient uptake and losses

The beneficial effect of rapidly released mineral nutrients into the soil will be short-lived if the system is unable to store such additions of soluble nutrients against leaching, run-off and erosion, or if the nutrients are not taken up. Nutrient uptake obviously relies on there being a pool of available nutrients, but after factors such as root biomass, density and distribution, uptake kinetics, and the production rate and nutrient content of the vegetation also play a part.

1.<u>Change in Uptake Dynamics</u>
The major differences between shifting cultivation systems and forests are:

a. the fine root biomass, which in annual cropping systems is often as much as 20 times less than that of forests(Szott *et al.*, 1991).
b. forests have a more uniform distribution of roots than most crop rooting systems which are planted in rows.
c. temporally, forest roots are constant whereas crop root systems are periodic (Palm *et al.*, 1995).
d. the loss of forest mycorrhizal associations
e. the biomass production of shifting cultivation crops is generally less than 10 t/ha/yr which is half that of a humid tropical forest (Young, 1989).

The above conditions coupled with high mineralisation and nitrification rates, may lead to the formation of large pools of available nutrients (Matson *et al.*, 1987; Saxena and Ramakrishnan, 1986; Montagnini and Buschbacher, 1989).

2. <u>Denitrification and leaching in the cropping phase</u>
The tight, closed nutrient cycle of natural tropical forests, described and discussed above, is broken leaving a high potential for leaching and gaseous loss from the pool of nutrients.

A difference of 233 kg ha^{-1} between mineralised N and N uptake during the first year of cultivation illustrates such losses (Mueller-Harvey *et al.*, 1983) but actual measurements of leaching or denitrification are few and are infrequently performed through the cropping season.

Upon conversion of forest to slash and burn agriculture, leaching loss increase from 14 kg N kg ha^{-1} to 43 kg N kg ha^{-1} and a denitrification increase from: 4 kg N kg ha^{-1} to 50 kg N kg ha^{-1} (Jordan *et al.* 1983).

Leaching is often the dominant process. Denitrification temporarily increases after clearance then falls to rates less than those in undisturbed forest soil, after only 4 months (Matson *et al.*, 1987). If leaching is the dominant process (Jordan, 1985), then the lost nutrients may be stored in the subsoil (Cahn *et al.*, 1992). Sorption of nitrate typically increases with depth, decreased pH, decreased organic matter, increased kaolinite and increased Fe / Al oxides (Black and Waring, 1979), and nitrate is not necessarily lost from the system.

Such losses from the nutrient stocks of the original forest are recognised to be greatly reduced if the slash is allowed to decompose naturally, as opposed to burning (Jordan, 1985; Scott, 1986). A combination of the two is practised in traditional partial clearing and flash burning (Andriesse and Schelaas, 1987). Research by Stewart (1994) on unburnt bush fallows on Entisols in Western Samoa showed some improvement of soil physical properties (lower bulk density) prior to cropping. Stewart suggested that unburnt bush fallows could be more sustainable than burnt slash, because the slower mineralisation means that nutrients are less likely to be leached and gaseous losses are reduced when burning is eliminated.

3. Site dependency

Studies by Jordan (1985) and Tulaphitak *et al.* (1985) have shown cumulative gains and losses of total nutrient stocks during slash and burn agriculture. Jordan observed that nearly all the mineral nutrients from the ash were initially retained by the clay surfaces, micropores, humus and root mat, but due to high soil permeability and the flat topography, leaching became the primary process for cation loss during the three years of cropping. In comparison the sub-humid site in Thailand studied by Tulaphitak *et al.* (1985) was hilly with less impermeable Inceptisols. More than 50% of the Ca, Mg, K and P gained through clearing and burning were lost through erosion and run-off at the onset of the rainy season during the 2 years. Here, as elsewhere, the lack of vegetation cover and the high rainfall intensity were prime factors in nutrient loss (Toky and Ramakrishnan, 1981).

The important conclusion from these and other studies, is that the amount and the causes of nutrient losses during the cropping phase are site dependent.

For slash and burn systems, Juo and Manu (1995) found the following conditions may accelerate losses from the ash-enriched, nutrient pool during the cropping phase:

a. The lack of continuous ground cover can exacerbate erosion and run-off losses, especially during rainstorms on sloping lands with less permeable soil.

b. The increased frequency of clearing and cultivation will lead to a gradual destruction of the soil macropore system thereby decreasing the quantity of by-pass flow and increasing the losses of mineral nutrients through leaching and run-off.

c. Burning and cultivation lead to gradual destruction of the root mat, decomposition of the humified organic matter from the original forest ecosystem and to a reduced contribution of nutrient cycling from organic and microbial processes.

Jordan (1985) in his research noted that despite leaching, nutrient amounts in the 'soil' were greater than those found in surrounding forest soil because decomposing ash and organic litter provided a continual supply washed down from the surface to replace the losses. Although this may occur at some sites it is important to look at changes to the ecosystem as whole. Comparing the total nutrient stock of the primary forest ecosystem with that of subsequent cycles of fallow forest succession reveals a gradual decline in the total nutrient stock of the ecosystem (Nye and Greenland, 1964; Scott, 1986; Jordan, 1985; Ramakrishnan, 1992).

4.5 Fallows

From an ecosystem perspective, the main function of the fallow phase is to allow the transfer of mineral nutrients from the soil back into the forest biomass. Due to losses in the cropping phase (volatilised, leached, eroded, harvested), recovery of the total nutrient stock during the subsequent fallows is lower than the original primary forest ecosystem. Successional vegetation retains nutrients in the system through rapid incorporation of nutrients into biomass, maintaining SOM, protecting soil structure and through reducing leaching and run-off (Harcombe, 1977).

1. Secondary vegetation recovery

Providing the cropping period is not too extended and significant soil erosion does not occur, there will normally be sufficient viable seeds and residual rooted stumps for the soil to rapidly redevelop the forest vegetation (Greenland and Okigbo, 1983). Such productive growth is possible on soil that had declining crop yields, as many native species utilise crop-unavailable nutrients through the mechanisms discussed in section on primary forest systems, and others specific to colonising species (Jordan, 1985).

The development of secondary vegetation varies greatly due to human interference (Maury-Lechon, 1982) and the inherent SOM, nutrient and moisture factors (Ewel, 1980). Disturbance that is intermediate (traditional shifting cultivation) allows tree species to redevelop rapidly. If the disturbance is more chronic then short life cycle grasses and herbs are favoured (Uhl *et al.*, 1982). There is initially a steady increase in productivity due to the rapid growth of pioneer herbaceous species, followed by fast-growing perennial species. A later shift to early successional tree species increases species diversity and enhances nutrient accumulation through increased rooting depth (Ramakrishnan, 1994)

2. Biomass dynamics

a)Total biomass - The first 15 yrs of secondary vegetation is characterised by rapid biomass accumulation (up to 100 t ha^{-1}). The rate appears to depend on soil fertility (Brown and Lugo, 1990).

b) Leaf biomass - The leaf biomass development is less soil dependent (Uhl and Jordan, 1984). The leaf area index can be expected to almost equal that of a mature forest within 5 - 6 years (Golley *et al.*,1976).

c) Root biomass - Total root biomass recovery may be slower (Berish, 1982), but the fine unsuberised root system (responsible for nutrient uptake) can almost completely redevelop in 1 year. Fine root biomass in a secondary forest was found to be 92 % of undisturbed forest fine root biomass, measured to a depth of 50 cm, after 1 year (Raich, 1980).

As a result of rapid regrowth, it has been hypothesized that nutrient loss during this biomass accumulation phase will be lower than that of mature forest ecosystems because of the high nutrient uptake rates (Vitousek and Reiners, 1975).

3. S.O.M. recovery

From models of global C flows, it is estimated that a period of 10 -15 years of secondary vegetation establishment is necessary to enable SOM levels to recover to 75% of primary forest levels (Buringh, 1984).

Brown and Lugo (1990) suggested recovery of SOM will be rapid under secondary forests due to high inputs of leaf litter and roots but Ramakrishnan (1992) suggests SOM will continue to decline for 5 - 6 years. Wadsworth *et al.* (1988) suggest a10 year decline as regrowth establishes as a result of low litter return initially, and decomposition rates remaining high during the colonisation stage. Ewel (1976), however, concluded that litterfall and leaf decomposition in a tropical rainforest succession increased with increasing age of vegetation to a maximum of 10 t ha^{-1} yr^{-1} in a 14 year old stand. Caro and Rudd (1985) studied leaf litter decomposition in primary and secondary forests and confirmed that slower decay rates in secondary species leaf litter were slower. Recomposition rates correlated well with the % lignin and % fibre in the leaves.

Szott *et al.* (1987) comparing secondary successional sites at different ages but on similar soils (Acrisols), found that the rapid regrowth of the vegetation affects soil properties through root growth and turnover, organic matter additions, vegetation-mediated changes in soil microclimate, and the canopy's ability to reduce the impact of rainfall on the topsoil.

Maximum humus levels have been recorded 10 years into a fallow (Ramakrishnan 1992), although Brown and Lugo (1990) estimated 40 - 50 years were required to return SOM to forest levels, regardless of the previous agricultural intensity. It has been postulated that secondary seral forests will eventually have greater SOM than mature tropical forests (Ewel, 1976). In addition to knowing the previous land use, knowledge of the bulk density and soil texture, especially the sand and clay ratios, are useful, as all influence the nature of the stabilisation and incorporation of SOM (Lugo *et al.*, 1986; Sanchez, 1976) and are necessary for an understanding of SOM dynamics under secondary forests (Brown and Lugo, 1990).

4. Savanna fallows

The overall increase in SOM is normally followed by an increase in C, N and P during the fallow (Jordan, 1985), fallowing during shifting cultivation being the main phase of N addition to the soil pool (Zinke *et al.*, 1978) through biological N fixation.

Regeneration of soil fertility is much slower under savanna and grassland than under forest. Savanna biomass production is recognised as being extremely varied (UNESCO, 1979). SOM levels are generally low, especially on the sandy soils typical of savanna regions (Jones, 1973; Kowal and Kassam, 1978). In some areas of central Africa, nutrient accumulation is so low it is inadequate to even support 1 or 2 reasonable crops. As a result, the Citimene system of collecting vegetation from surrounding savanna and piling it for burning has developed in certain areas. To supplement this animals provide manure, which is again collected and applied to certain fields (Ruthenberg, 1976). Crops in savanna areas are often legume based, as is the fallow phase, but despite this, N fixation under savanna conditions appears to be generally slower than under forest vegetation (Greenland, 1977) and contributions to the N economy appear to be low.

5. Fallow nutrient accumulation

The accumulation of nutrients in the plant tissue will provide the ash fertiliser for the next cropping phase. Such fallow accumulation is closely associated to species diversity, length of fallow and the inherent soil fertility (Juo and Manu, 1995).

Weeds and grasses are common early on in the succession. *Mikania micrantha*, an aggressive exotic weed studied by Swamy and Ramakrishnan (1987), found in the 'jhum' systems of north east India, can dominate fallows for the first four years of fallow. It is subsequently suppressed by fast growing shrubs and trees. K uptake is very high in *M. micrantha* and so it performs an important K conservatory role, as K is highly mobile and easily leached in more humid tropical environments.

Bamboos form an important component of the secondary succession of many tropical rainforests (Rao and Ramakrishnan, 1989). Their N, P and K contents are generally much higher than other species in the community, and they can remain in the secondary vegetation about 25 - 30 years.

K and other elements immobilised by pioneer species are transferred to successional species upon death. The pioneer and successional species continue to take up the remaining nutrients, causing a continuation of the decline in Ca, Mg and possibly K soil stocks during the cropping phase for several years after the site is abandoned (Jordan, 1985).

High rates of nutrient incorporation into leaf biomass and turnover rates of elements in litter fall appear to plateau at an early stage of forest development (Uhl and Jordan, 1984).

The young, colonising trees accumulate a high proportion of the total nutrient capital present in the mature system. As Bowen and Nambiar (1984) state, young trees accumulate nutrients, in contrast to mature trees that tend to re-use elements. Lambert and Turner (1986) found that nutrients were accumulated in higher concentrations on a previously disturbed site than a primary forest; they suspected this may be a conservatory mechanism. The specific combination of structural properties modifying decomposition and nutrient accumulative capacities in secondary species may act to conserve nutrients. The tissue nutrient concentration of the secondary forest will decrease as biomass C increases (Brown and Lugo, 1990).

Vitousek (1984) proposed a measure of within stand nutrient cycling efficiency (NUE) by measuring the ratio of litter mass production to the mass of nutrients contained in the litter. Nutrient turnover is shown to be higher in secondary forests, reflecting faster rates of decomposition and uptake of nutrients than in mature forests (Vitousek and Reiners, 1975; Brown and Lugo, 1990). The NUE for P in secondary forests ranged four-fold in relation to comparatively small variation of P inputs from litter. This suggests P is tightly conserved by trees on some sites compared to N which has high availability in most forests (Yavit and Wieder 1988; Anderson and Spencer, 1991; Robertson, 1989).

6. Rotational fallow and sustainability

Studies of native cultivation systems by Zinke *et al.* (1978) and Sabhasri (1978) on the lua forest fallow system on latosols in N. Thailand, and by Ramakrishnan (1992) on the jhum agroecosystems in north east India have highlighted the sustainability of systems using differing lengths of fallow. The Lua system may be sustainable in the long term without fertilisation given that nutrients apparently reaccumulate sufficiently for cropping every 10 years. With less than this length of fallow, it is believed that fertility status will decline (Zinke *et al.*, 1978) as recovery is slow between the 3rd and 7th year, then rapidly accelerates.

Ramakrishnan notes the reversal in transfer of nutrients from soil to biomass early in the successional phase when litterfall begins, either through leaf drop or the complete turnover of the early herbaceous vegetation at around the 10th year of fallow. Hence, it is believed the 10 year jhum cycle is critical for sustainability. Current 4 -5 year jhum cycles lead to frequent nutrient losses under low fertility levels, and will eventually lead to severe degradation unless there is a change in management (Ramakrishnan, 1992).

4.6 Land Clearance Methods

Mechanised forms of forest clearance are being practised more commonly, and for a wide range of subsequent land uses. Several different machine methods and practices are employed depending upon the future land use and the socio-economic factors. These have been comprehensively reviewed by Lal *et al.* (1986). Which method is employed greatly affects the residual vegetation, microclimate, soil structure, nutrient reserves, the hydrology and recovery potential of the site (Lal *et al.*, 1986).

Traditional shifting cultivation (slash and burn) causes least soil disturbance of all the forest clearance methods, and problems of runoff and soil erosion are generally minimal (Lal, 1986). The resultant soil quality and productivity have been demonstrated to be superior than in other land clearance methods (Seubert *et al.*, 1977; Couper *et al.*, 1981). However, the selection of slash and burn as the land clearing method may be restricted because of the comparative economics on a larger scale, combined with frequent labour shortages in more remote clearance areas. The result is that mechanized land clearance is being increasingly used (Ferreira Netto and Destoca, 1969; Lal, 1986).

Changes in soil physical properties have been noted during land clearance. The magnitude of the alteration in soil physical properties depends on many soil and environmental factors, but of major importance are (Lal, 1986):

- the method of land clearance,

- antecedent soil physical properties (soil moisture content)
- the density of vegetation cover

Forest clearance leads to certain soil physical alterations irrespective of method employed:

> a) When surface cover is removed, raindrop impact destroys the surface aggregate structure, loosening fine soil fractions, so that clay particles and other colloids are preferentially removed from the surface layer by overland flow and seepage water (Martins *et al*, 1991). Thefine particles may block micropores (Lawson *et al.*, 1981) and perhaps also macropores (Spaans *et al.*, 1989) increasing the soil erodibility (Luk, 1979). A critical factor is the difference between levels of surface litter covering the soil, reducing rain impact (Wiersum, 1985).
>
> b) Similarly, all cleared land undergoes alteration of soil structural properties as a result of ultra desiccation and the SOM decline. This affects structural stability, crusting and water acceptance of the soil surface (Cunningham, 1963; Lal, 1986).

4.7 Mechanized clearance

Damage to soils by mechanical clearance and subsequent erosion depends on site factors (forest type, slope, season), the clearance method employed (tree pusher, shear blade) and the operators skill in machine control (Dias and Nortcliff, 1985; *et al.*, 1985).

Soil changes are dramatic with mechanized clearance, the types of soil deterioration and the degree of alteration are described below:

> a) Compaction - Mechanised methods cause much greater soil compaction, up to 70 cm (Janssen and Wienk, 1990) or even 80 cm in depth (Van de Weert, 1974), when compared to hand clearance methods (20-30 cm). Aina (1984) suggested that changes in hand cleared sites may be as a result of the rain exposure, decreased organic matter content discussed above, and reduced biological activity upon clearance.
>
> b) Porosity - The porosity of soil alters greatly when machine cleared (Hulugalle *et al.,* 1984), macro and mesopore volume decreasing as the micropore volume increases (Van de Weert, 1974). Macropores have been reportedly eliminated to a depth of 30 cm. As a result of the greater micropore volume, the soil moisture at field capacity may increase, but root permeability and aeration decreases to such an extent that root growth may be impeded.
>
> c) Moisture retention - Drastic reduction in moisture retention at low suction occurs after mechanical clearing (Hulugalle *et al.*, 1984; Cunningham, 1963). Compaction-induced decrease in the soil moisture storage capacity is one reason why annual crops may suffer periodic drought stress on mechanically cleared land (Lal, 1986).

d) Infiltration - Associated with these characteristic alterations is a drastic decrease in infiltration. Mahier (1980) reported tractor disturbance reduced steady state infiltration capacity from 154 to 0.28 mm/h, with low infiltrability persisting 5 - 9 years after logging. Studies by Seubert *et al.* (1977) on an Ultisol in Yurimaguas, Peru showed that cumulative infiltration over 2.5 hours was 12 times greater on land cleared by slash and burn techniques compared to bulldozed land.

The soil structural changes described above can greatly influence the movement of nutrients to roots (diffusion and mass flow):

i. Beneficially, through the increase in soil water percent / volume, and through the increases in unsaturated hydraulic conductivity.
ii. Detrimentally, through limited root development, less effective precipitation and poor soil aeration (Van de Weert, 1974).

e) Erosion - Experiments at IITA indicate significant interaction between method of clearance, post clearing management and the degree of runoff / erosion. Comparing different methods revealed a sequence of decreasing severity in the total runoff amount and peak runoff rate:
tree pusher rake > shear blade > manual clearing > traditional farming.
Massive soil erosion can occur but can be greatly reduced with correct clearance method, operational methods and post clearance agro-engineering (El-Swaify and Dangler, 1982). Shear blading can result in 20% of the erosion loss suffered after tree pusher/ root rake clearing (IITA, 1985)

Shearblading slices the tree off as opposed to tree pushers that disrupt the roots and a wide area of soil. Chain felling was thought to cause less soil degradation than bulldozer and straight blade techniques, as limited traffic during felling should reduce soil compaction. No such advantage was observed under field investigation in dry to slightly moist conditions (Barber and Romero, 1994) though it was speculated that the advantage may appear under different antecedent moisture conditions and with other forest types and operators. (Ghuman and Lal, 1992)

f) Soil Chemical Alteration - The chemical changes under slash and burn clearance have been described previously. Mechanical clearance can decrease the soil nutrient status permanently and decrease the SOM content through scraping of the surface soil during windrowing (Reynolds, 1990), and topsoil disruption from general bulldozer activity. The ash input from a burn can double the level of exchangeable bases, whereas there is little change in cations in bulldozed areas (Seubert *et al.*, 1977). Exchangeable Al has been observed to increase in the topsoil of mechanically cleared land, in contrast to the pH increase and subsequent decrease in Fe and Al availability following slash and burning (Seubert *et al.*, 1977).

Windrowed areas benefit from improved soil fertility capacity at the expense of the rest of the cleared area. The benefit of a deeper topsoil, greater organic matter and CEC is visible through greater productivity that can last up to 8 years after the windrow has been pushed aside (Janssen and Wienk, 1990).

The reduction in soil fertility can be very visible in crop performance and yield. Seubert *et al.* (1977) observed that yields in bulldozed plots were 1/3 of those in slash and burn plots. Lal (1981) did not see such a drastic difference, but there was a visibly lower yield on mechanically cleared land. Crop yields are more drastically altered on Ultisols and Oxisols, when mechanized clearing removes a substantial amount of the biomass and top soil nutrients of an already inherently low fertility soil (Lal, 1987).

4.8 Chemical clearance

Chemical clearing is thought to have potential especially in savanna regions with low tree density (Carter, 1974). However, some mechanised operation is still required to fell and windrow the dead/dying trees. Poisoning of trees with subsequent inter-tree crop planting without clearance has been investigated but lower yields were obtained compared to other methods as a result of shading and no ash input (Ahn, 1970). The low cost per area of land cleared (Liefstingh, 1965), and the possibility of off-setting the ash advantage through fertiliser application (Ahn, 1970), gives this method future research potential.

4.9 Commercial Logging

Commercial logging is responsible for 1/4 of the annual loss of primary rainforest around the world (Tyler, 1990), and is often the primary reason for clearance before other land uses take over. The highest forest loss from logging activity occurs in S.E. Asia, which accounts for nearly half of the world's tropical timber export; Japan consuming 40% of the world's hardwood supplies (Swinbanks, 1989).

1. Forest damage

Loggers commonly use one of two methods: clear felling (complete tree clearance) or selective logging.

Selective logging can often be employed as few trees in natural tropical forests are commercially viable. Intensive logging in lowland forests extracts perhaps as little as 10% of the timber volume. Felled trees are generally emergents, with large crowns linked by liana and as a result there is considerable damage to other trees when they are felled. Up to 55% of the forest may be damaged by selective timber extraction (Whitmore, 1984) and in addition, a substantial proportion of the non-commercially viable forest is removed for roads and skid tracks. Nicholson (1979) estimates that after logging between 15% and 50 % of the forest consists of bare soil or badly damaged forest. The level of damage can be much reduced through improved method and procedure (Whitmore, 1984; Jonkers, 1987).
Logging may be a severe disturbance, but it is short-term compared to the other land uses (Jordan, 1985).

2. Nutrients

Nutrient extraction through timber removal is negligible in relation to the total nutrient capital although for low fertility soils (Oxisols) K and Ca are seen as critical elements to monitor given the amounts in the forest biomass and the very low ambient annual inputs (Poels, 1987). Soil property dynamics were measured by Gillman *et al.* (1985) in an Australian rain forest following logging; they recorded a decrease in organic C of 15%, but the capital levels of N, Ca and Mg had not changed for the site as a whole.

3. Soil erosion

Increases in runoff, erosion, streamflow and sediment transport are broadly proportional to the surface area disturbed (Nations and Komer, 1983; Dosso *et al.*, 1981). It should be noted that even partial clearance may severely increase the erosion hazard:

-Infiltration rates on roads and skid tracks may be 7 to 21 times less than in the natural forest as a result of compaction (Whitmore, 1984).

-Gullies frequently form along such routes, increasing the length of ephemeral channels feeding the drainage network (Greer *et al.*, 1990; Anderson and Spencer, 1991).

Such compacted skid tracks and roads were believed to be the main cause of a 6 to 12 fold increase in sediment loss in an Australian rain forest after logging (Gilmour, 1971).

In logging operations the loss of nutrients and sediment downslope through surface erosion may be reduced by the logging debris and 'patchy' vegetation (Cassels *et al.*, 1985).

4. Subsequent land use

Indirectly, commercial logging causes deforestation beyond mechanical and extractive disturbance. As a result of crude infrastructure construction other types of land use can exploit these partially disturbed areas, potentially introducing complete forest clearance. The FAO estimate 2/3 of all primary forest clearance is only possible as a result of the roads and general infrastructure built for commercial logging (WWFN, 1988). Over 90% of the 40 to 50,000 km^2 of closed forest land that is logged each year, is subsequently used for crop land (WRI ,1987).

4.10 Continuous cropping

Soil properties are drastically influenced by continuous intensive farming, much more so than by shifting cultivation. Many researchers have quantified the effects of continuous cropping upon the chemical and nutritional properties of soil following natural vegetation clearance.

1. SOM change

Investigations on a series of soil groups have shown a sharp decline in the level of SOM during the first few years with or without fertilizer application following land clearing and cropping (Adepetu and Correy, 1977; Cunningham, 1963; Juo and Kang, 1989; Kang, 1993b). The pattern of SOM decline is classically represented in work by Brams (1971) on rice crop cultivation in Sierra Leone, and Olu Obi (1989) on cassava cultivation in Nigeria (Fig. 4.2.). Again, initial SOM decline is rapid, associated with mineralization of the active fraction. Brams (1971) found that rate of organic matter loss reduced in the 3rd year, and was stabilized by the 5th. Both studies suffered from increased acidity, and an increase in soluble Al.

Kang (1993b) was able to reduce the level of organic C loss through fertilization and crop residue retention in a continuous cultivation study for 10 years on an Entisol in S. Nigeria. However, this could not prevent a decrease in soil organic C, pH, Ca and Mg levels. Aina (1979) reported an overall collapse in soil structure with the decrease in SOM. Lal (1976) studying maize cultivation with and without tillage, reported the smallest SOM declines in the no-till maize crops, and the largest with tillage for cowpea crops. There were parallel changes in soil moisture retention and surface water infiltration rates, possibly further indications of aggregate deterioration in the topsoil.

Continuous cultivation in conjunction with residue removal and tillage (Follet and Schimel, 1989), has been shown to induce rapid mineralisation of SOM, by disrupting macroaggregates, and also to increase mineralisation of SOM previously within protected aggregates (Tiessen and Stewart, 1983).

2. Soil chemical properties

Continuous cropping also results in a sharp decline in soil pH in many tropical and sub-tropical soils. Soil acidity is a major factor in Ultisol crop production in the tropics (Sobulo and Osiname, 1986), though a decline in pH was also observed on Alfisols.

The use of mineral fertilisers in intensive agriculture can induce soil acidity, with pronounced effects experienced under moderate to heavy rates of application (Backe and Heathcote, 1969; Kang and Juo, 1986). Kang (1993b) observed that soil acidification and the continuous application of fertilizer led to pronounced manganese toxicity in cowpea crops on an Entisol. On kaolinitic and oxidic soils in high rainfall areas, long-term cultivation induces this pH decline and with it a corresponding increase in soluble and exchangeable Al in the soil (Friessen *et al.*, 1981; Sanchez *et al.*, 1983; Kang and Juo, 1986).

The decline in SOM and soil structure, combined with acidification leads to a reduction in the CEC and increased losses of exchangeable Ca and Mg (Kang and Juo, 1986). After several years of cropping the use of lime appears to be necessary, even on high base status Alfisols (Kang, 1985). Intermittent doses of lime, as opposed to a single heavy dose, better alleviates the problems of imbalance in Ca/Mg and Ca/K on acid soils inherently low in K and Mg (Sobulo and Osimane, 1986). Such applications on kaolinitic Ultisols have provided only a short residual effect (Friessen *et al.*, 1981; Sanchez *et al.*, 1983).

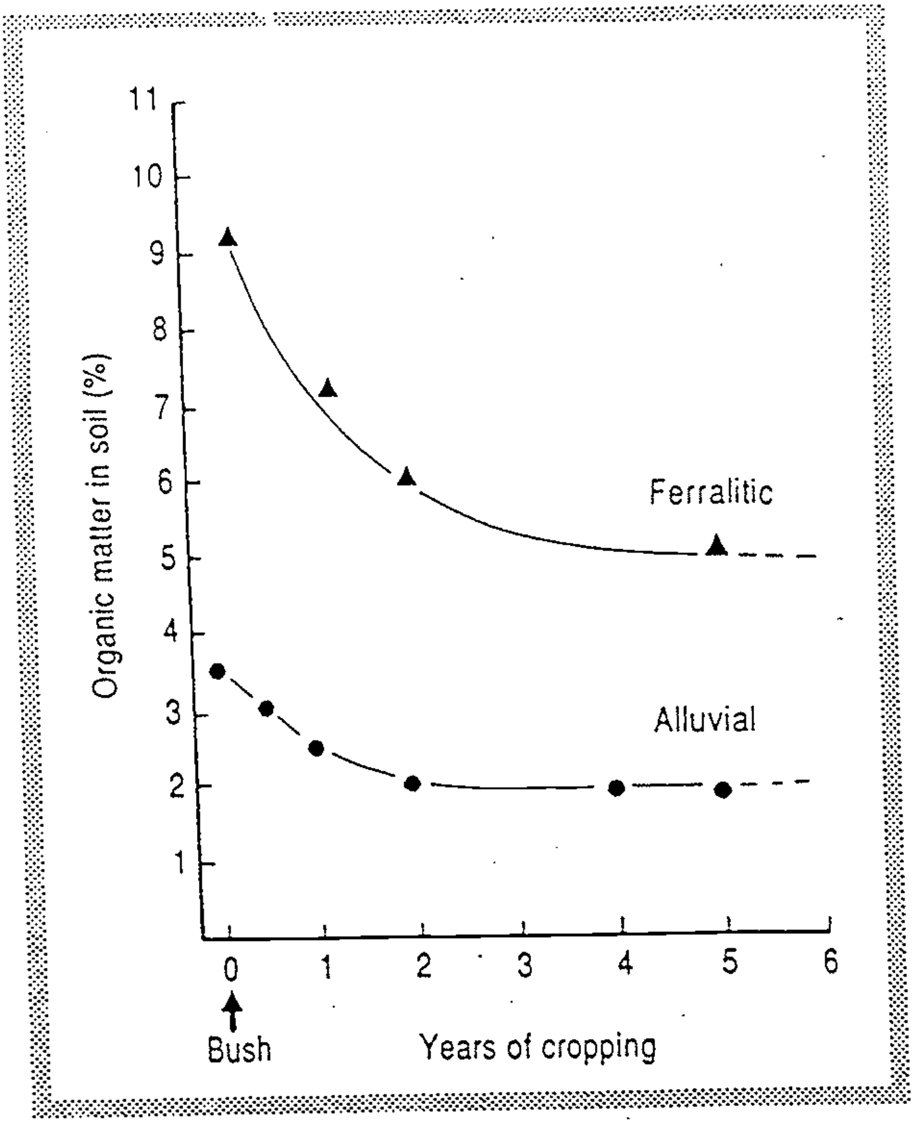


Fig. 4.2 Decline in organic matter content of two tropical soils after clearing natural vegetation cover. After Brams (1971).

3. Fertilizer application

There have been fertiliser application studies in continuous cropping since the early 1970's in Yurimaguas, Peru (Villachica *et al.*, 1976; Jordan, 1985). In this study fertiliser application was able to improve the yield and prolong the period with an acceptable yield (Sanchez *et al.*, 1983; Nicholaides *et al.*, 1985; Kang and Juo, 1986), but was unable to arrest the declining yield after a period of several years cropping. Reasons for such yield declines were suggested as:

1) insufficient rates of fertilization
2) poor germination
3) increased insect attack (pathogen build up)
4) soil compaction
5) soil acidity (important in other situations)

If only macronutrients are replaced during continuous cropping through fertilization, eventually micronutrients may become critical constraining factors (Jordan, 1985). Such applications should be considered, as they have been shown to substantially improve yields (Villachia and Sanchez, 1978; Jordan, 1985).

In soils containing low activity clays, SOM is the major store for nutrients and the basis of the CEC (Sobulo and Osiname, 1986). Savanna soils generally have low levels of SOM and as a result, low soil N content. Consequently, almost all N requirements of the crops have to be externally supplied. K nutrition is also influenced by SOM (Sobulo and Jaiyelo, 1977) though the type of parent material may be more important in determining requirements for K additions to the soil. A soil from sandstone parent material has inherently low K reserves so any depletion of SOM will severely reduce the amounts of available K (Heathcote and Stockinger, 1970). Subsequent application of K supplements to such a sandstone-derived soil must be timed to meet crop demand as there is likely to be a very low CEC.

4. Soil Management

SOM plays an important role in the management of fertility in fragile tropical soils. Management practices to reduce the depletion of SOM, and soil compaction are possible, for example:

a) Reduced tillage systems. Compaction occurs from mechanized clearance, cultivation and continuos cropping. Kayombo and Lal (1993) reporting tillage systems in Africa, noted that soil type was extremely relevant in determining the response of management practice. Oxisols generally have good structure and can be cultivated for many years without aggregate disruption (Acland, 1972). Ultisols and Alfisols have generally less desirable structural properties with clay accumulation in subsurface layers being a diagnostic feature of these soils. The presence of argillic horizons may result in shallow rooting. Cultivation frequently leads to rapid infiltration decline, surface crusting, low to moderate available water capacity, poor structural stability and typically only 1-2% SOM with a rapid turnover (Young, 1976). If this occurs on sloping lands, continual cultivation may lead to substantial erosion and compaction hazards, resulting ultimately in low crop productivity (Lal, 1984, 1985; Stocking and Peake, 1986). In African upland areas in the sub-humid and semi-arid regions soils with dense subsurface layers and naturally compacted soil are common(McCartney *et al.*, 1971). Exposure following clearance of vegetation may lead to impermeable crust development from rain drop impact and, as a result, runoff may increase (Hoogmoed and Stroosnidker, 1984).

b) Crop residue mulches and cover crop mulches play an important role in maintaining SOM and productivity (Kang, 1985; Feller *et al.*, 1987). Crop residues provide substrate to the microbial biomass, resulting in increased soil aggregation through mucigel and gum production. Cover crops increase macro-porosity infiltration rate, soil moisture retention, saturated hydraulic conductivity and decrease bulk density (Kayombo and Lal, 1993). Organic C, total N, pH, CEC and exchangeable bases are also increased through cover crops (Juo and Lal, 1977; Kang *et al.*, 1990). Growing deep-rooted legumes may alleviate soil compaction, but only in non-severe cases (Hulugalle and Lal, 1986). For more severe compaction, a period of cover crop duration >1 year is required. Alternatively, compaction can be alleviated by mechanical means (Lal, 1989a).

Short (4 -5 month) legume fallows can provides N, organic matter and reduce acidity (Amon and Adetunji, 1973; Sobulo and Osiname, 1986). Alternatively, incorporation of a legume crop into the rotation, may achieve the same (Jones, 1974).

Researchers at IITA in Ibadan, Nigeria have been able to maintain high crop yields continuously on an Alfisol through the adoption of a leguminous component to the crop rotation, provision of nutritional needs (fertilizer) of the crops in relation to changes in soil properties, and the retention of crop residue (Kang, 1985). In effect the degree of crop and soil monitoring was extremely high, enabling rapid response to deficiencies. A number of field plot experiments with intensive and continuous cropping have been able to sustain high yield through the judicious use of fertilizers, small quantities of lime and conservatory soil management (Juo & Manu, 1995). Whether these will successfully transfer to larger field application, especially under mechanised methods, is questionable because compaction and surface sealing may become more serious yield limiting factors than nutrient and lime inputs (Lal *et al.*, 1986).

4.11 Pasture land

Cattle ranching is a major cause of tropical forest destruction, particularly in the rainforests of Latin America (Park, 1991). It requires an extensive area of land and clearance for cattle ranching continues at about 20,000 km^2/yr (Friends of the Earth, 1989). Soil fertility and pasture yield can decline rapidly after ranching begins, only a few years of intensive cattle grazing can destroy the physical soil structure The Ultisols and Oxisols common in Latin America are inherently infertile and cattle grazing is often neither a suitable nor sustainable use of converted forest land (Goodland, 1980).

1. Nutrient dynamics

There are reported cases of beneficial effects on the soil chemical properties after several years of cultivated pasture conversion (Serrao *et al.*, 1978). This long term study by Serrao and co-workers on infertile Oxisols and Ultisols in the Amazon region of Brazil, has enabled the construction of models highlighting trends in the SOM and nutrient dynamics.

Under forest conversion through manual slash and burn, it is possible to maintain the raised levels of soil pH, CEC, exchangeable Ca, Mg and K, as observed throughout the 13 years of the *Panicum maximum* cultivated pasture (Figs 4.3 and 4.4).

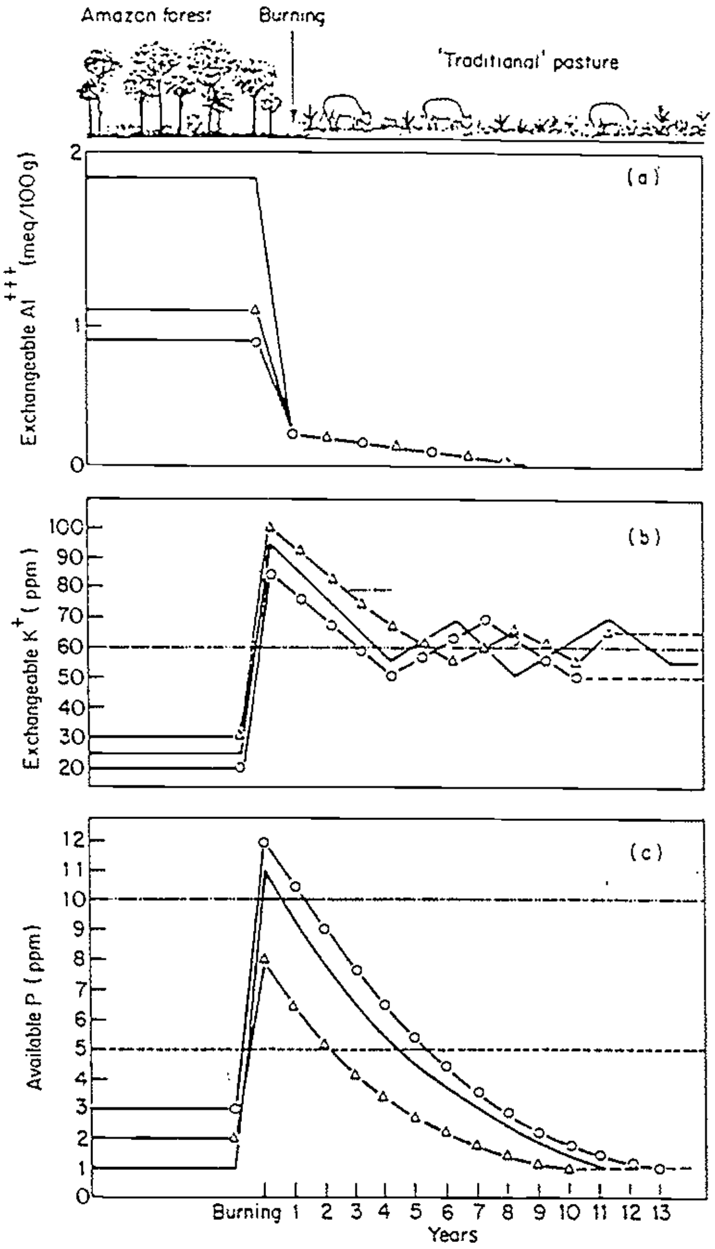


Fig. 4.3 Changes in available or exchangeable aluminiun (a), potassium (b), and phosphorus (c) following conversion of forest to *Panicum maximum* pasture: —, yellow latasol (oxisol). very heavy texture; o — o, red yellow podzolic (ultisol), medium texture; Δ — Δ, dark red latosol (oxisol). medium texture; —·—, standard critical level (4) – – – –. proposed critical level. [Adapted from Souza Serrão *et al.* (1978).]

2. S.O.M. dynamics

SOM is seen as a good indicator of soil condition that reacts quickly to external influences, and is expected to fall following forest clearance (Detweiler and Hall, 1988). Following the burn, as the decomposition rate of the forest humus exceeds the organic inputs from the establishing pasture, SOM does indeed decrease. However, over several years the process is reversed and SOM increases as the grass root debris humifies (Serrao *et al.*, 1978; Cerri *et al.*, 1991; Lugo *et al.*, 1986; Andreaux *et al.*, 1990).

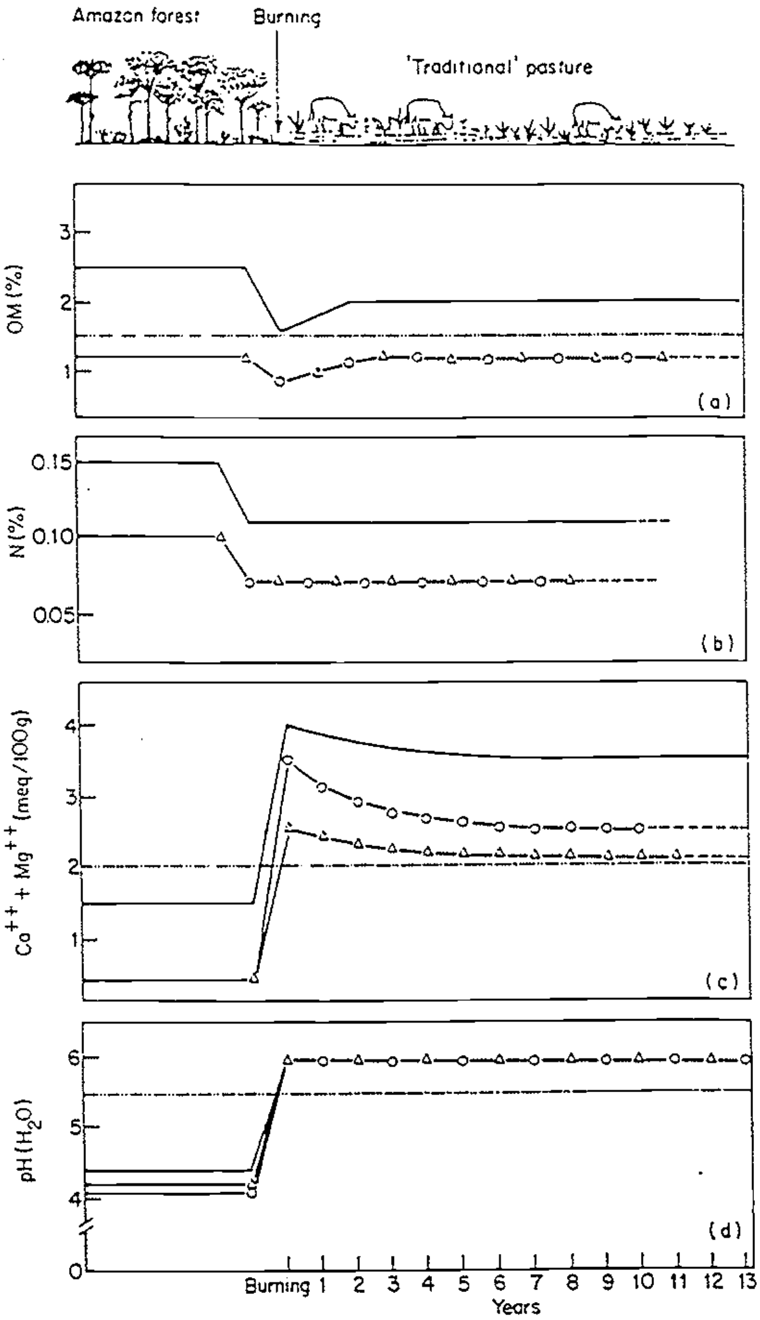


Fig. 4 . 4 Changes in soil organic matter (a), nitrogen (b), calcium plus magnesium (c), and soil pH (d) following conversion of forest to *Panicum maximum* pasture: —, yellow latasol (oxisol), very heavy texture; o — o, red yellow podzolic (ultisol), medium texture; Δ — Δ, dark red latosol (oxisol), medium texture; -..-..-, critical level (4). [Adapted from Souza Serrão *et al.*, (1978).]

The degree of SOM recovery varies Cerri *et al.* (1991) recorded SOM restoration to levels similar to adjacent undisturbed rain forest on a clay rich Oxisol at Manaus, Brazil. In contrast Bonde *et al.* (1991) reported no change in SOM content after 8 years under tropical pasture in the Brazilian Amazon. It has been recorded that abandoned pasture may have SOM comparable to the tropical forest that preceded it (Weaver *et al.*, 1987; Lugo *et al.*, 1986). Such results contrast with reported total C decline following conversion to a tropical cropping system, because of the difference in above and below ground organic inputs. However, the reported total soil C maintenance may mask a decline of the smaller labile (active) fraction (lower SMC/TC ratio) so that a large passive pool of forest-derived SOM masking the dynamics of the microbial biomass. Microbial carbon and biomass analyses suggest that the same pastures may be beginning to decline (Bonde *et al.*, 1991; Palm *et al.*, 1995).

3. Phosphorus decline

Figure 4.3 shows that available P suffers the biggest decline after burning and after several years (5 yrs) it becomes the most critical nutrient for sustaining the pasture yield (Serrao *et al.*, 1978). This decline occurs despite the maintenance of a high pH value so it is likely be caused by a depletion of the total P stocks (Jordan, 1985).
Tropical pastures are commonly burned when the user notes a marked productivity decline. The rationale for this practice is that it sustains higher levels of pH, Ca and Mg, and brings the P back into an available form. Unfortunately, each burn results in a smaller increase in P because as the stock of Ca, K and Mg declines, each burn results in a smaller pH increase (Jordan, 1985). On certain pastures such a burn only alleviates the declining productivity for 2-3 months in the following growing season (Serrao and Homma, 1993).

An incomplete forest slash and burn, could provide a slow decomposing nutrient source in pasture conversion. Buschbacher *et al.* (1988) showed that unburned woody slash can be as important as the soil for the P, K and Ca supply in light pasture systems. In the cases studied, it enabled faster vegetation regrowth upon abandonment.

The potential decline in pasture productivity can be avoided, and the benefit of the ash inputs maintained, through:
- P fertilisation,
- establishing a legume grass mixture and
- restricting grazing to the optimum level.

4. Overgrazing

There is also land degradation through soil compaction and soil erosion, associated with overgrazing (Fearnside, 1978). Vegetative cover is reduced, root biomass decreases and compaction by trampling increases the bulk density thereby increasing the susceptibility and rate of soil erosion, especially sheetwash (Eden *et al.*, 1991). In drier areas, overgrazing may lead to desertification as it is the pasture vegetation that holds the sandy soil in place.

5. N deficiency and legume introduction

Tropical soils with grass pastures frequently suffer from an N deficiency because of:
- large N losses from concentration of animal excreta, leading to a negative N balance
- N immobilisation in the soil as a result of grass residue with a high C:N ratio that decomposes slowly.

Establishing a legume grass mixture balances the N budget as legume residues have a lower C: N ratio and decompose rapidly thus stimulating N mineralisation. Competition with the grass sward may lead to high fixation levels.

Assuming that approximately 10% of ingested N is removed in animal products, and that 50% of the N in excreta is lost from the system, it has been estimated (Cadisch *et* *al.*, 1994) that in a Brazilian *Stylosanthes spp./ Andrpogon gayanus* mixed sward that at least 70 kg N ha^{-1} are needed to be fixed in order to balance the N losses from such a system (Figure 4.5).

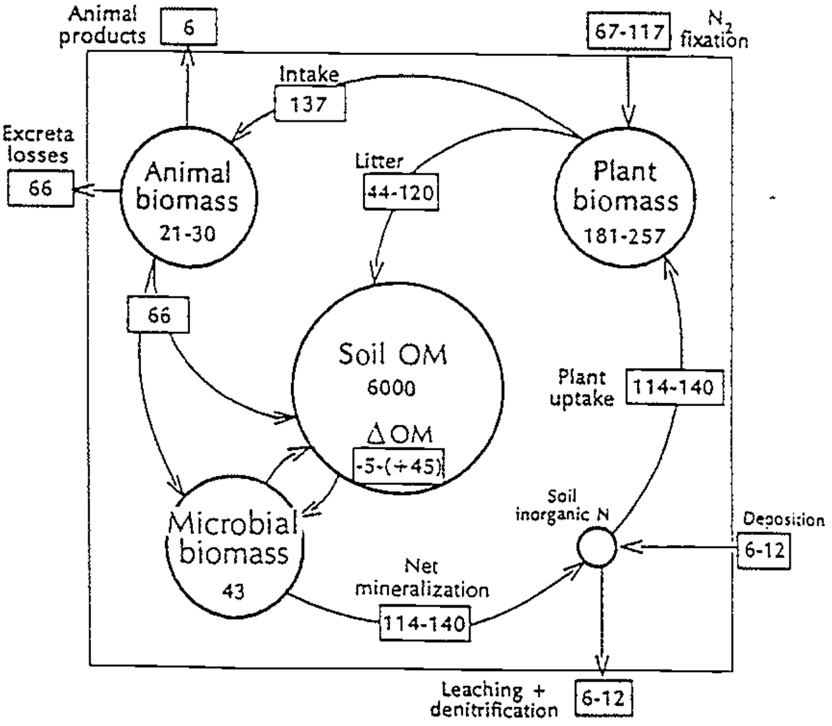


Fig. 4.5 The nitrogen cycle in a grazed *Stylosanthes* spp./*Andropogon gayanus* pasture in the Brazilian Cerrado (from Cadisch *et al.*, 1994a). An input from N_2-fixation of at least 70 kg N ha^{-1} is required in order to ensure the system is sustainable in the long term, i.e. that inputs and outputs from the system are in balance such that there is no depletion of the soil organic matter (OM) N pool. (Circles represent the main pools of N in the system with the amount of N given in kg N ha^{-1}; the rectangles represent the major N fluxes with the amount given in kg N ha^{-1} yr^{-1}; ΔOM = predicted annual change in organic matter N pool.)

Legume introduction to native pastures in sub-Saharan Africa has proved difficult due to communal grazing land rights (Tothill, 1986). Planted grass / legume pastures have mainly been successful on commercial farms, particularly for dairy production (Kategile, 1985; Haque and Tothill, 1987). Similarly, the introduction of legumes to pastures in tropical regions of Australia has led to sustainable production systems (Fig. 4.6).

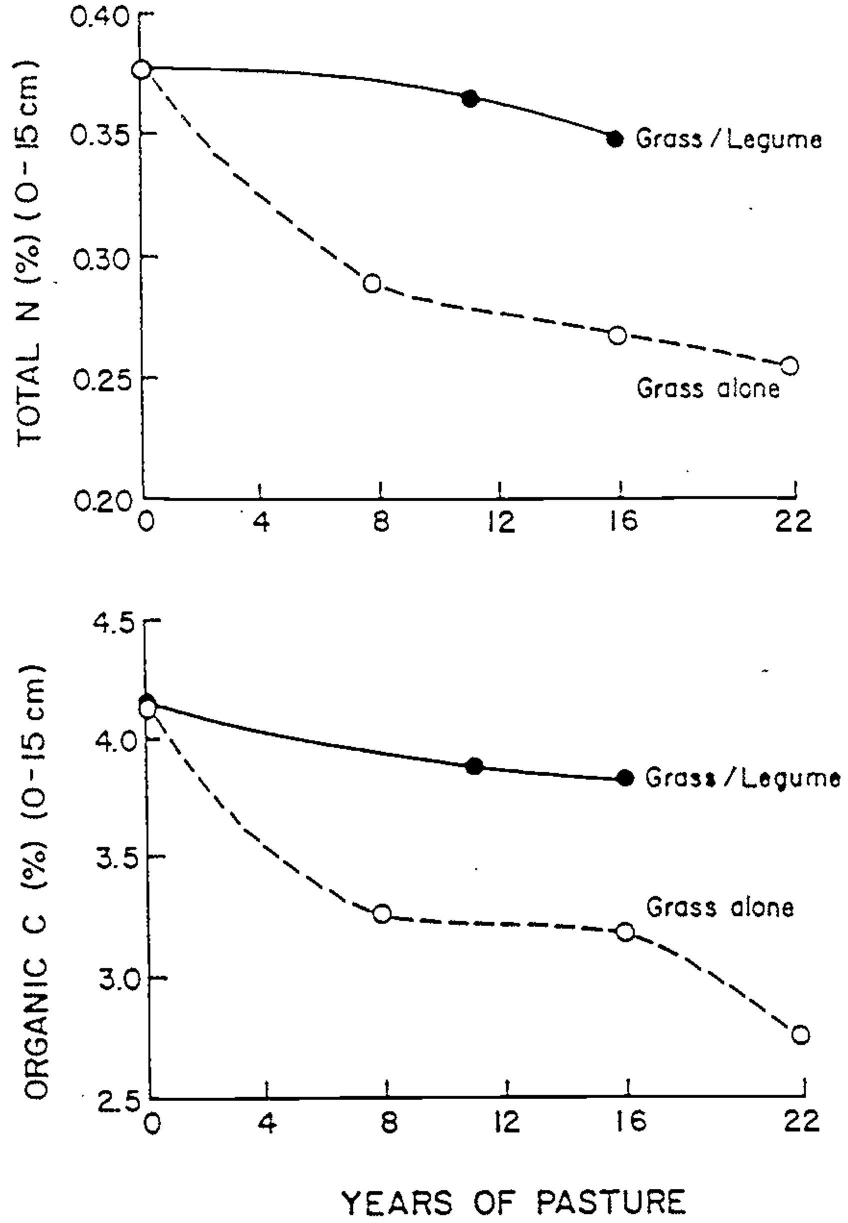


Fig4.6 Long-term effects of unfertilized guineagrass pastures, with and without *Centrosema pubescens*, on the topsoil organic matter after clearing a rainforest in South Johnstone, Australia. Source: Adapted from Bruce (1965).

6. Soil constraints in Latin America

The success of legume / grass mixture pastures relies on introducing plants adapted to the soil and climatic limitations rather than changing the soil to meet the plants nutritional requirements (Sanchez, 1982; Spain, 1979).

Oxisol and Ultisol soil constraints that pasture species must tolerate are:

a) Al toxicity - CIAT has collected germplasm tolerant to high levels of exchangeable Al from acid infertile soil regions (Figure 4.7).

b) Low P availability - P is the single most expensive input required to improve pastures in Oxisol / Ultisol savanna soils. It is possible to select plants with lower P requirement. Fortunately, Al tolerance and low P tolerance often occur jointly in plant species (Salinas, 1978; Sanchez, 1982). There is no evidence that low P tolerant species are unable to supply the cattle's P requirements (CIAT ,1978, 1979).

c) Water stress - Al tolerant roots develop deeper and so automatically have a water uptake advantage (Gonzalez *et al.*, 1975; Sanchez 1982).

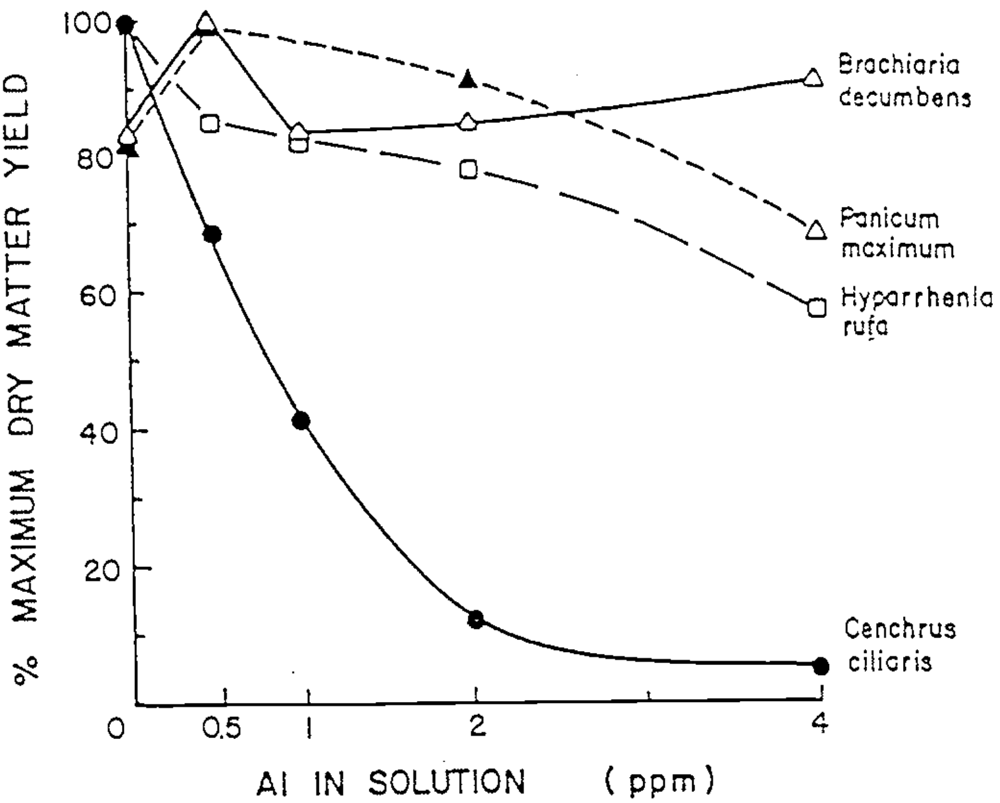


Fig4.7 Differential tolerance to Al in culture solution by four tropical grasses. Source: Spain (1979).

d) Insect and disease attack - Many of CIAT's legume species are native to Latin America so natural enemies are abundant.

e) Tolerance to burning - Accidental or managed burning occurs often in savanna regions.

Despite such research and productivity success, it is estimated that at least half (10 mill ha) of the forest converted to pasture in Brazil over the past 25 years has reached the advanced stages of degradation. If appropriate technology were applied to just 50% of the current forest converted to pasture in the Brazilian humid tropics, livestock production could meet demands until at least 2000 (Serrao and Homma, 1993). Such technology involves mechanisation, improved forages, fertilization and weed control, and once introduced continued investment is necessary.

At the moment fertilizer application in many tropical areas (regardless of other technological investment) is not practical, due to high cost and poor supply. As a result the best source of nutrients remains the standing tropical forest. Opening up more land is seen as cheaper than prolonging the use of existing ranchland through such fertiliser application, soil conservation and disease control (Eden, 1991; Caufield, 1985). A form of 'shifting pasture cultivation' has developed, which poses a great threat of ecological damage, in terms of biomass, biodiversity, soil and water losses, and possibly global climate change (Salati, 1990 cited by Serrao and Homma, 1993).

4.12 Plantations

There are two general types of plantation:

a) perennial tree crop plantations; including short rotation crops, such as pineapple and sugarcane, as well as tree crops such as bananas and rubber.

b) plantation forestry, involving lumber, pulpwood and fuelwood production or even environmental protection.

The establishment of plantations will always lead to a loss of biodiversity, but it is recognised that the long term effects of forest conversion to perennial crops such as plantations are not as drastic as those from clearing to arable land use (Lal, 1986).

A. Perennial tree crop plantations

The changes in microclimate, surface runoff and soil erosion observed immediately after vegetation removal are generally minimised after the perennial crop is established (Lal, 1986)

1. Soil erosion

Soil erosion risks in plantation crops are generally less than those under arable land use (Ollagnier *et al.*, 1978; Lal, 1986). The extent of erosion will differ according to the clearance method used and the production/management system implemented. Typically, establishing rubber or oil plantations causes more erosion than coconut or cocoa plantations (NRC, 1993). Susceptibility to erosion is reduced markedly if prior to and during seedling establishment the bare soil is protected by a cover crop, such as *Mucuma* or *Pueraria*. This performs a thermoregulatory role preventing severe disruption of the soil fauna (Martin, 1986) and improves soil physical structure and SOM content whilst preventing weed and grass growth. Severe soil erosion is still commonplace under improperly managed plantation crops (Lal, 1986).

2. Nutrient extraction

Extractive plantation or tree crops have significant effects on nutrient dynamics and nutrient capital when harvested. Soil quality degrades through the immobilisation and removal of crucial cation elements in the pods, beans and nuts etc (Adejuwon and Ekanade, 1988). This is further aggravated as the rate of soil nutrient return to the topsoil in monoculture plantations is less than the nutrient uptake by the vegetation. Such nutrients must be replaced to sustain yield and minimise depletion. Rubber imposes a relatively small nutrient drain, whilst oil palm plantations impose a high drain of nutrients (Tiffen and Mortimore, 1990) Krebs *et al.* (1974) compiled a series of regression equations between soil properties and the duration of cultivation over 22 years for sugarcane and coffee in comparison to pastureland. Soils under coffee showed significant reductions in SOM and N, whilst Ca and Mg concentrations did not alter. In contrast, the sugarcane plantations suffered a decrease in soil Ca and Mg concentrations and an increase in Al.

There have been reports of increased exchangeable Ca in plantation soils but this is attributed to slow decomposition of trunk/stumps left over from clearance (Tinker, 1968; Anderson and Spencer, 1991).

3. Crop tree / legume tree mix

Fruit plantations with a sustainable economic yield have been developed in several tropical regions without using a fallow period or fertiliser supplements to replace extracted nutrients. This has only been possible when the plantation crop has been grown together with other trees, commonly nitrogen-fixing legumes (Jordan, 1985).

In coffee plantations, large leguminous shade trees have increased the availability of, the roots being able to penetrate deeper, possibly utilising and incorporating nutrients into the cycle that are beyond the reach of the coffee plants (Beer 1982; Sanchez *et al.*, 1985; Michori, 1993). Similarly, in Sri Lankan coconut plantations leguminous trees (*Gliricidia, Leucaena*) are used as a source of mulch to enhance soil fertility, organic C content, water holding capacity and the resultant nut yield (Liyanage *et al.*, 1992). These measures, along with terracing and other conservatory practices simply mitigate the losses from harvesting and erosion.

Stable and increasing yields are sustained through the extensive use of agrochemicals and the development of higher yielding varieties (Pee, 1977; NRC, 1993). Examples being the rubber and oil palm plantations of the Malaysian peninsular successfully established for almost a century (Vincent and Hadi, 1993).

B) Plantation forestry

The FAO (1993) define plantations as forest stands established artificially by afforestation on land previously forested or otherwise. From this the calculated ratio between the annual rate of deforestation and forest plantation establishment is 1 : 8.5. However, for the Asia and Pacific region it is estimated the annual area covered by new establishing plantations is half the annual deforested area (FAO, 1993).

1. Soil deterioration

Deterioration in physical and nutritional soil properties have been reported in East Africa under timber plantations by Lundgren (1978). He reviewed the literature, and effects of fast growing tree plantations on soil dynamics in tropical highlands and subtropical regions and proposed a conceptual model of SOM, nutrients and bulk density dynamics at 7 different stages of development (Fig. 4.8). He showed that without soil conservation measures, a decline in yield of man-made forests and other plantation crops will occur due to progressive soil deterioration. Deterioration in the form of decreased SOM, nutrient levels, loss of topsoil structure and porosity was likely with faster degradation in lowland humid and sub-humid tropical conditions than in sub-tropic / or tropical highlands.

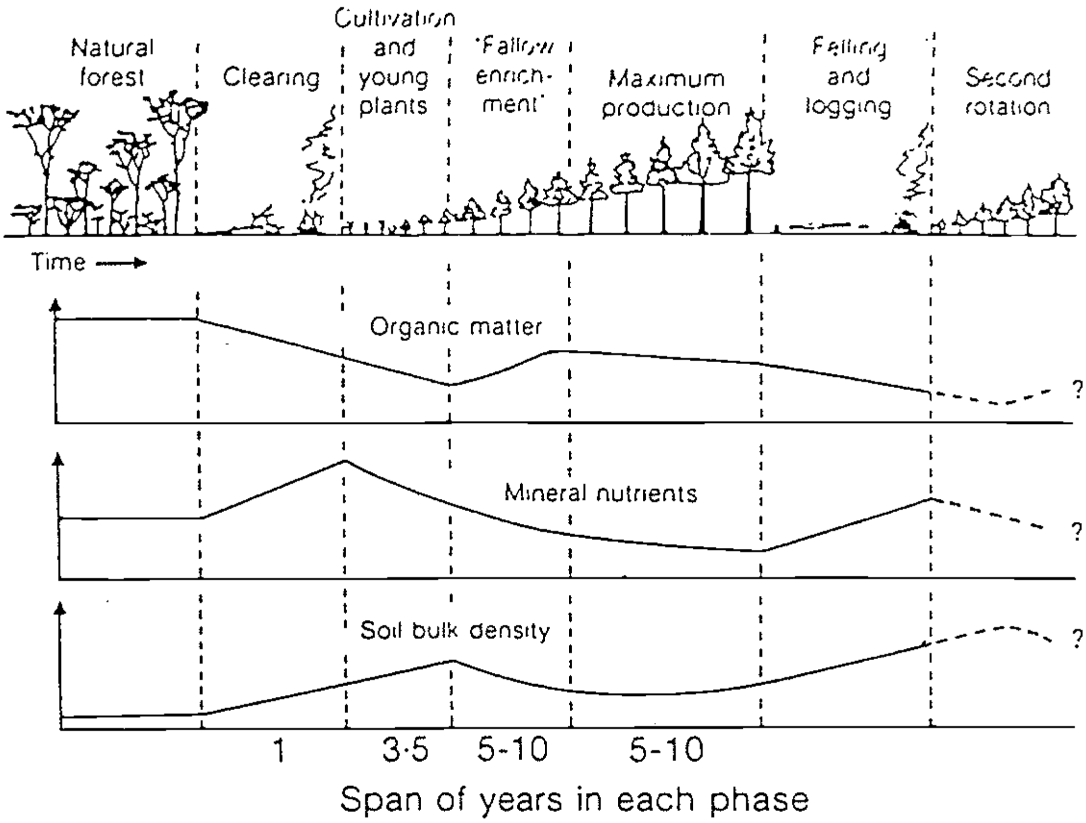


Fig. 4.8 Lundgren's model of the effect of clearing natural forests and growing fast-growing tree plantations on soil properties in the tropics (from Lundgren 1978).

Sanchez *et al.* (1985) found unexpected maintenance of soil chemical properties and an increase in Ca below *Gmelina arborea.* Facilities such as continual protective canopy cover, larger biomass and nutrient stocks and recycling ability explained this. Growth of tree crops, such as *Gmelina arborea*, can be very sensitive to soil compaction (Johnson, 1976), and fast-growing tree species can create nutrient imbalances and declining soil fertility by immobilising large quantities of K, Ca and N (Chijioke and Mayer, 1980).

In a comparative study by Lugo (1992), Caribbean pine plantations (*Pinus caribaea*) were found to have less nutrient uptake from the soil and greater above ground nutrient use efficiency, than native forest stands. When balanced with slightly lower below-ground root production and biomass, the total primary productivity in this case was equal to that of the native forest. Lugo (1992) compared about 70 native / plantation forest studies and concluded that generalizations about structure and function cannot be made without considering the climatic, soil, biotic or temporal characteristics of the ecosystem.

2. Soil hydrology
Establishment of timber plantations has been shown to be effective in conserving soil and water through reduced runoff and erosion (Hardjono, 1980; Lal, 1986). Timber plantations will inevitably be harvested inducing changes in ecosystem water balance, soil physical properties and microclimatic parameters. The magnitude of such changes depends on the timing and quantity of timber removal. A rise in the water level is likely when deep rooted trees are removed (Lawson *et al.*, 1981) so it might be assumed that establishment of deep rooting trees leads to a decline in the water table.

3. Plantations for Reclamation
Without constant maintenance plantations will not remain as monocultures and native secondary species will rapidly establish. This tendency for diversification can be manipulated to instigate land reclamation. Forest plantations are being seen as a means of rehabilitating abandoned and degraded soils in tropical ecosystems (Sanchez *et al.*, 1992; Dagar and Singh, 1994). Plantations of native or exotic species that can adapt to stressful conditions may be able to reverse the degradation process. This reversal of degradation occurs as a result of the development of extensive root systems which stabilise the soil, increasing SOM through greater litter input (Lowry *et al.*, 1988) fine root turnover and decomposition (Montagnini and Sancho, 1990), moderation of soil pH and general improvement of soil status (Sanchez *et al.*, 1985; - Cruz and Luna, 1992). With the above effects, and microclimate modification and canopy development, the recruitment, survival and growth of the native forest species is facilitated (Uhl *et al.*, 1982; Prasad and Pandey, 1989; Soni *et al.*, 1989).

A successful example of reclamation with tree plantation of a degraded, low-P, acid soil exists in South Sumatra where a site infested with 'alang-alang' was reforested with rubber trees (Benites, 1990). The plantation acts as 'foster ecosystem' (Lugo, 1988) accelerating development of genetic and biochemical biodiversity in degraded sites. Parrota (1992) monitoring soil under an *Albizia lebbek* plantation established on degraded soil over 4 years, noted soil carbon and nitrogen underwent a 1.9 fold and a 1.64 fold increase (respectively). Available P and exchangeable cation levels were similar to the degraded soil control.

5. AGROFORESTRY

5.1 Agroforestry Systems

Agroforestry is a 'land use system in which woody perennials are deliberately grown on the same piece of land as agricultural crops and / or animals on the same unit of land either in some form of spatial arrangement or in sequence' (Lundgren, 1982). The term woody perennial encompasses trees, shrubs, bushes, palms, bamboos and rattans etc., often collectively referred to as multipurpose trees and shrubs (MPTS).
There are many thousands of agroforestry-based land use systems (Nair, 1989) but to illustrate the variety of different tree / crop arrangements, the 20 distinct agroforestry practices listed by Young (1989) are presented.

A. Mainly AGROSILVICULTRUAL (trees with crops)

Rotational systems:
- planted tree fallows (agriculture)
- taungya (forestry)

Mixed systems:
- trees in cropland
- plantation crop combinations - with upper storey or lower storey tree and shrub crops or with herbaceous crops.
- tree garden systems - home gardens or multi-storey tree gardens.

Zoned systems:
- hedgerow intercropping (alleys)
- boundary planting
- trees for soil and water conservation - as barrier hedges, on grass strips, bunds or terraces
- shelterbelts, windbreaks and shade trees
- trees for biomass transfer

B. Mainly SILVOPASTORAL (trees with pasture and animals)

Mixed systems:
- trees on rangelands or pastures
- plantation crops with pasture

Zoned systems:
- live fences - as barriers or multipurpose
- fodder banks

C. FORESTRY PLANTATIONS
- woodlots with agroforestry objectives
- reclamation plantation for re-establishing agriculture - on eroded land, saline soils, or on sand dunes

D. SPECIAL AGROFORESTRY APPLICATIONS
- entomoforestry - beekeeping with agroforestry
- aquaforestry - trees with pisciculture
- trees for water management

These systems are mixed, zonal, layered (simultaneous systems), or sequential:
a) Mixed systems tend to be used where competition effects are not severe.
b) Zonal systems can minimise competition when it occurs.
c) Layered systems are the most complex, typified by the Home garden system.
d) Sequential systems separate the components in time.

The trees have both a productive and service function:-

a. Productive - trees provide fuelwood, building materials and high quality dry season fodder. They can also be an important source of income generation from poles, timber, fruits, medicines, resins and gums.

b. Service - at the farm level, service functions are soil fertility improvement and/or maintenance, the reduction of wind and water erosion, enhanced microclimate, livestock containment through living hedges, and demarcation of internal and external boundaries. At a larger scale, trees can improve the hydrological cycle in watersheds, and maintain soil, insect, plant and wildlife biodiversity. A further role is the sequestration of carbon in above and below ground biomass with the secondary effect of reducing rates of deforestation and hence further C emission (Unruh *et al.*, 1993).

5.2 Soil Agroforestry Hypotheses

The extensive agroforestry literature implies that appropriate agroforestry systems can: '*improve soil physical properties, maintain S.O.M., and promote nutrient cycling*'. This forms the basis of the initial soil-agroforestry hypothesis (Sanchez, 1987), but as universally applicable statement it is probably incorrect.

Hypotheses relating to the ability of tree-based systems to conserve or improve the properties of tropical soils have been formulated. Young (1989a), presented 10 hypotheses and, since this initial formulation, further hypotheses have been added (Van Noordwijk & Dommergues, 1990; Wilson, 1990; Ong *et al.*, 1991). Sanchez (1995) listed 16 hypotheses, together with their current status (Table 5.1).

Table 5.1 The Agroforestry Hypotheses (Source and citations from Sanchez, 1995)

Hypothesis	Status and references
1. Agroforestry systems can control soil erosion	1. Proven in contour hedgerows and multistrata systems (Roose, 1970; Lal, 1989; Young, 1989b; Alegre and Fernandes, 1991; Banda *et al.*, 1994; ICRAF, 1994; Juo *et al.*, 1994; Kiepe & Rao, 1994)
2. Agroforestry systems can maintain SOM at levels satisfactory for soil fertility	2. Not proven. Too simplistic, since there are no reliable SOM levels related to satisfactory soil fertility. SOM increase has been detected temporarily in sandy soils under alley cropping (Lal, 1989; Kang *et al.*, 1990) but not for other soils (Rao in press). Relevant proof should be in terms of functional SOM pools in relation to system nutrient uptake and overall productivity.
3. Agroforestry systems maintain more favourable soil physical properties than agricultural systems	3. Partially proven for soil under contour hedgerows in relation to adjacent cultivated fields (Van Noordwijk *et al.*, 1992; ICRAF, 1994)
4. N-fixing trees can substantially augment N inputs in agroforestry systems	4. Proven (Ladha *et al.*, 1993). Limited quantification of N-fixation by legume spp. and subsequent biomass N accumulation and return to the soil via litter.
5. Trees in agroforestry systems provide deep nutrient capture from subsoil layers that are inaccessible to crop roots	5. Proven for deep rooted nitrate capture in oxic subsoils with positive charge (Hartemink *et al.*, in press; ICRAF, 1995). Not yet proven widely and unlikely to be relevant in other infertile subsoils.
6. Agroforestry systems can lead to more closed nutrient cycling and to	6. Not quantitatively proven. Highly probable in many systems, but data not available.

more efficient use of nutrients and less leaching losses	
7. The cycling of bases accumulated by trees in agroforestry systems and returned to the soil as litter can help reduce soil acidity.	7. Proven for litter high in Ca and Mg in non-agroforestry systems (Sanchez *et al.*, 1985). Decomposition of leaf litter produces metabolic organic products that temporarily complex Al in the soil solution, thus decreasing soil acidity, for short time periods (Davelouis *et al.*, 1991; Wong *et al.*, in press)
8. Agroforestry is a useful component of systems for the reclamation of degraded soils.	8. Too general, probably will be proven in many circumstances. Proven for saline and alkaline soils (Singh *et al.*, 1994). Proven for N depleted soils of Eastern Zambia with Sesbania fallows (Kwesiga & Coe, 1994).
9. The role of tree roots is as important as that of above-ground biomass in soil fertility maintenance.	9. Not proven. An important research topic.
10. Shade from tree canopy improves soil biological activity and N mineralization.	10. Proven (Wilson, 1990; ICRAF, 1993).
11. Roots of N-fixing trees have more nodules when in close contact with roots of non N-fixing plants. This may lead to direct transfer to the non-nodulating plant.	11. Not proven. Highly controversial.
12. Annual crops are unable to use all water stored in the soil.	12. Proven for shallow rooted crops (Ong *et al.*, 1995)
13. The combination of trees and crops generally enhances rainfall water use.	13. Proven (ICRAF, 1994; Ong *et al.*, 1995).
14. Because agroforestry systems use more water than annual cropping systems, they should increase primary development.	14. Being tested, depends on competition.
15. There is less competition between tree and crop species that develop canopies at different times.	15. Proven (Dalal, 1974).
16. Competition for water in agroforestry systems can be reduced by modifying the spatial arrangement of trees.	16. Proven (ICRAF, 1994)

As yet, most of the hypotheses are only supported by sparse or indirect evidence. Contradictory results and conceptual errors are frequent (Sanchez, 1987; Young, 1989b).

Most evidence for the soils - agroforestry hypotheses is observational, qualitative or extrapolated from other systems (Sanchez, 1987). Quantitative data on the effects of trees on soil properties has frequently been based on natural systems or plantation forestry (Lundgren, 1978; Sanchez et al., 1985; Vitousek and Sandford, 1986).

In addition to contradictory evidence and conceptual errors, the best documented and successful agroforestry systems appear to be located largely on fertile soils. Successful cacao, rubber, coconut and oil palm agroforestry systems have been located on fluvents, Andisols or on high base status Alfisols (Russo and Budowski, 1986). Similarly, the homegardens of Asia (Michon *et al.*, 1986), and Africa (Fernandes *et al.*, 1984) are located on regionally very fertile soils. However, quantitative evidence and detailed analysis of homegarden sustainability and efficiency is sparse (Torquebiau, 1992).

Despite these reservations, agroforestry is considered especially applicable to marginal soils with severe physical demands or drought constraints.

The hypothesis is that trees in agroforestry systems will, like natural ecosystems (Vitousek and Sandford, 1986), efficiently transfer nutrients from the trees to the crops is supported by evidence of higher crop yields and soil nutrient levels where trees have recently been removed (the basic principle behind shifting cultivation - Nye and Greenland, 1960).

5.3 Spatial concentration of resources (nutrients)

A specific effect of woody plants in resource-poor environments is the redistribution of resources leading to areas of concentration and areas of depletion (Breman and Kessler, 1995). The spatial concentration of water and nutrients under woody canopies is achieved partly at the expense of the open field. It should be noted that woody plants frequently "build onto" resource concentrations from other processes, such as higher clay content areas leading to greater SOM (Geiger *et al.*, 1992), or old subsoil termite mounds (Brouwer *et al.*, 1993; Breman and Kessler, 1995). Shmida and Burgess (1988) postulate that in (semi-) arid regions, biological fluctuations will be lower and total productivity higher with strong spatial variability (i.e. there will be local concentrations), compared to an even distribution of resources (nutrients).

Enhanced surface soil nutrient properties under *Faidherbia. albida* are well recognised (Weil and Mughoghio, 1993; Kamara and Haque, 1992). Depommier *et al.* (1992), comparing soil characteristics under and away from *F. albida* canopies in 4 parklands clearly showed (averaged) increases in SOM (45%), total N (48%), available P (26.5%), as well as other enhanced chemical characteristics.

Positive tree-crop interactions have been reported repeatedly (Vandenbelt, 1992). Millet and sorghum crops growing within a 5-10 m radius around mature *F.albida* trees were shown to yield two to three times more than crops grown out of the influence of the canopy (Bonkoungo, 1992).

Various processes associated with woody plants in semi-arid ecosystems can influence below-canopy nutrient availability (Breman and Kessler, 1995 Fig. 5.1):

1) redistribution of available nutrients within the ecosystem through lateral root nutrient uptake, or efficient external cycling.

2) reduction of nutrient losses through reducing wind/water erosion and leaching.

3) Enrichment of the nutrient pool of the ecosystem as a whole through a)atmospheric deposition, b) deep nutrient uptake, c) N-fixation, d) rhizosphere interactions (mycorrhizae) and e) animal / bird excreta.

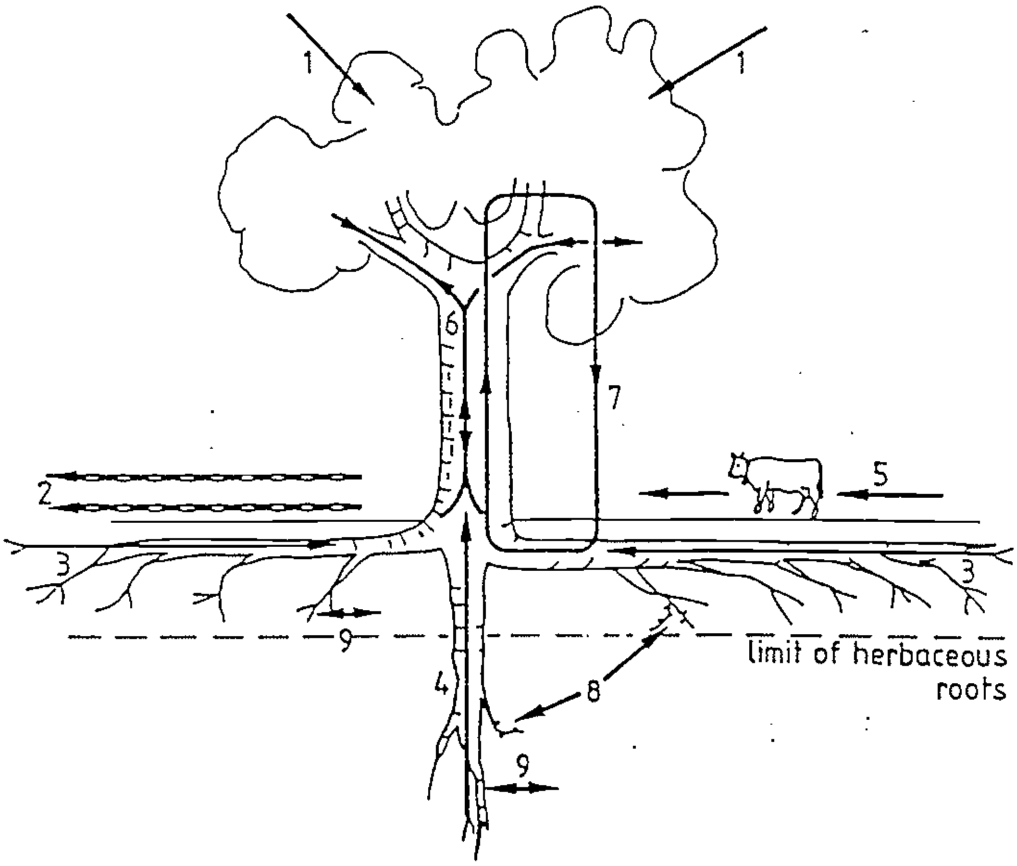


Fig. 5.1 Woody plant related processes influencing nutrient availability: *1* atmospheric deposition and interception; *2* losses by wind and water; *3* uptake by lateral roots; *4* uptake by deep roots; *5* deposition by animals; *6* internal recycling; *7* external recycling; *8* N_2 fixation, *9* rhizosphere interactions

There is no evidence of N-fixation or observed nodule action for *F. albida* in the field, but N accumulation/maintenance and high pod N concentrations suggest that it occurs. N_2 fixation by woody legumes is estimated at 0.1 kg ha^{-1} yr^{-1} and 0.6 kg ha^{-1} yr^{-1} for the Sahel and Sudan semi-arid zones respectively (Breman and Kessler, 1995) which is insignificant for nutrient enhancement.

Phosphorus is widely considered to limit primary production in most semi-arid regions. There is no evidence to assume that the presence of endomycorrhizas increases P availability. They merely facilitate greater P uptake although deep P uptake from weathered sources is negligible (Burnham, 1989). Most semi-arid agroforestry systems will require additional P inputs to sustain yields (Breman and Kessler, 1995).

Deep nutrient uptake is assumed to play a crucial role *F. albida* tap roots can reach to over 30m capturing soil moisture in periods of drought (Alexandre and Ouedraogo, 1992). However in semi-arid areas, physical and chemical root barriers are widespread (Szott *et al.*, 1991) and subsoil nutrient concentrations are low (Kellman, 1979), especially for P and bases, so deep nutrient uptake is unlikely (Breman and Kessler, 1995).

Reduced nutrient losses

Breman and Kessler (1995) suggest that the most important functions that woody plants perform to improve nutrient availability are those that reduce losses from water erosion and leaching. Reduction of water erosion results from improved SOM content, and reduction in wind erosion comes about through low ratio of trunk height to canopy diameter and the production of shallow roots. Leaching is reduced by the high root density and deep rooting, the deep roots allowing herbaceous plants to benefit from increased nutrient availability (Table 5.2).

Avoidance of over-exploitation of the woody plants by, for example, over-grazing is important but is difficult to achieve and is probably the reason why most agrosilvicultural systems in semi-arid climates do not reach their estimated potential crop production values.

Lateral uptake

Lateral uptake - Studies on Karite (*Vitellaria paradoxa*) and Neme (*Parkia biblobosa*), both non-N fixers, suggest that they have efficient nutrient-capture systems that redistribute locally available nutrient resources through a laterally extensive root system (Kater *et al.*, 1992; Kessler, 1992; Tomlinson *et al.*, 1995; Kessler and Breman, 1991). In such cases, competition appears to be low despite tree roots occupying the same soil zones (Radersma, 1994). The density of the tree fine feeder roots is 10 - 100 times lower than that of the herbaceous roots (Breman and Kessler, 1995) and in dry conditions roots are not strongly competitive and rhizosphere depletion zones are small (Marschner, 1986).

This may not always be the case. Belsky (1994) looking at the shade, nutrient and tree/grass competition effects of *Acacia tortilis* in Kenyan savannas, concluded that shade, tree litter, and animal droppings increased below-canopy productivity (Belsky *et al.*, 1993) but this benefit was cancelled out when savanna trees compete intensely for below-ground resources at wetter sites, where root systems terminate at the crown limit. At drier sites competition under the canopy was reduced as roots extended farther into the open grassland.

Table 5.2. The maximum effects of various processes associated with woody plants in the Sahel and Sudan zones on nutrient availability for primary production of a mixed vegetation, considering the effects in the canopy area and canopy cover in the vegetation as in the pre-drought situation, in comparison to a vegetation without woody plants (Breman and Kessler, 1995).

Process	Zone	
	Rainfall: 150-600 mm canopy cover: 2-20% (Sahel zones)	Rainfall: 600-1200 mm canopy cover: 15-30% (Sudan zones)
1. Redistribution / concentration		
atmospheric deposition - origin dust	+	0
- origin ocean	0	0
- origin fire	0	+
Capture of wind blown organic material[a]	+	+
nutrient concentration by lateral roots	+	++
deposition by animals	+	+
2. Reduction of losses		
Decreasing - wind erosion[a]	+	+
- water erosion[a,b]	0 - +	+ - ++
- leaching[c]	+	+++
- fire (volatilisation)[c]	+	+
Internal recycling	+	++
External recycling	+	++
3. Enrichment		
Nutrient uptake by deep roots[d]	0	+
N_2 fixation	0	+
Rhizosphere interactions[d]	0	+

0 = unimportant; negligible effects.

+, ++ and +++ = N increase by 1-5, 5-10 and >10 kg $^{-1}$ ha $^{-1}$ yr $^{-1}$; P increase <10% of these values.

[a] For shrubs highest value.

[b] Depending on nutrient leaving by rivers (lowest value) or internally redistributed (highest value).

[c] For N in particular.

[d] For P in particular.

Efficient external cycling

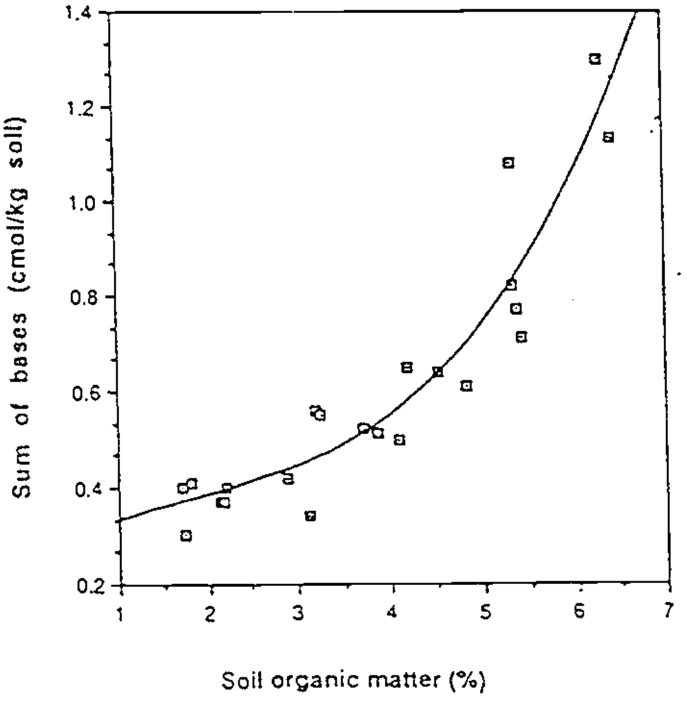
Very efficient external cycling is observed with *F. (Acacia) albida*, in which the canopy develops over the dry season and the leaves drop as the rains commence (Joly, 1992). Low lignin / N ratio and moderate polyphenolic / N ratio (Reed *et al.*, 1992) lead to rapid decomposition as the rains progress and when the crop is most demanding. For example 112 kg N ha^{-1} was mineralised over 4 months under *F. albida* canopies compared to 42 kg N ha^{-1} in the open (Rhoades, 1995) on a fertile alluvial soil in Malawi. Furthermore, the canopy provides microclimatic advantage to the crop below through reduced soil / leaf temperatures and reduced transpiration rates over the midday period (Vandenbelt and Williams, 1992), and increased soil moisture (Rhoades, 1995).

SOM improvement

Campbell *et al.* (1994) studying the influence of indigenous trees on soil fertility in Zimbabwe concluded that fertility improvement was not at the expense of the surrounding area, though obviously dependent on rooting morphology of the species. The mechanism that played a major role in this semi-arid savanna system was SOM improvement from increased litter and greater microbial activity leading to higher rates of nutrient flux. Because organic matter is the prime determinant of exchange capacity in sandy soils, the greatest increase in cation levels was recorded on the [dysotrophic] sandy soils. Trees can diminish soil nutrient availability through internal cycling, but increased flux cycling can off-set this decrease (Radersma, 1994).

Montagnini and Sancho (1990) studied the influence of several Costa Rican native trees on soil properties of experimental plantations in the humid tropics on a fertile Entisol. A close relation between organic matter content increase and the sum of bases was observed (Fig. 5.2).

Fig 5.2 Relation between soil organic matter and base content, soils sampled in August 1988.



Are such examples of nutrient-enhanced, tree-crop benefits restricted to the drier semi-arid areas? Observations indicate diminishing crop benefits and their eventual disappearance approaching the sub-humid tropics (Sanchez, 1995).

It is obvious that several processes are instrumental in nutrient and productivity enhancement for various tree species, in different climatic environments and soil types. These need to be separated and quantified, for agroforestry application (Sanchez, 1995). There are already conclusions and recommendations for improving sustainability in sylvopastoral and agrosylvicultural systems (Breman and Kessler, 1995).

5.4 Agroforestry Processes for productivity and sustainability

Growing trees in association or rotation with annual crops or pastures is generally perceived to have beneficial effects on soils. Agroforestry systems are expected to increase biological and / or economic productivity by extracting larger quantities of nutrients per unit time and / or area than the cultivation systems they replace.
Therefore, in order for such agroforestry systems to increase productivity and be sustainable:

1) nutrient losses must be lower,
2) inputs must be larger,
3) and / or recycling must be more rapid. (Szott *et al.*, 1991)

5.4.1 Nutrient losses

Factors determining rates of leaching, sediment and runoff losses are complex, and there are methodological difficulties in quantifying such fluxes, hence data is unreliable and scarce.
Data does suggest that leaching losses are likely to differ between certain soil groups, as found in natural forest ecosystems (Szott *et al.*, 1991).

Soil erosion (conservation)
Stabilising the soil resource through planting closely spaced trees on slopes, reduces erosion through the action of two processes:

- As a physical barrier of stems low branches and superficial roots against running surface water.
- Through improving soil structure and hence infiltration rates (ICRAF, 1994; Dalland *et al.*, 1993).

There is scientifically acceptable evidence that contour hedges and alley cropping effectively control erosion as long as hedges provide an effective barrier (Young, 1989a; Lal, 1989b; Kiepe and Rao, 1994; ICRAF, 1994; Juo *et al.*, 1994; Fujisaka *et al.*, 1995). In comparison to monocropping, retention can be observed in alley cropping systems probably due to the increased density and better distribution pattern of the roots (Hauser, 1990). However, nutrient losses in alley cropping systems may be larger than in natural systems, due to less extensive root systems and periods when soil cover is reduced (Szott *et al.*, 1991).

It is expected that erosion and runoff in economically or biologically enriched fallows and homegardens would be similar to natural forest systems as a result of the similar soil cover and transpiration rates.

Soil erosion loss does have fertility implications(Comia *et al.*, 1994) and not simply because of physical sediment removal. Erosion and runoff accounts for half of the negative N and P balance in a typical Rwandan farm (Smaling, 1993; Sanchez, 1995). Soil erosion is undeniably a major cause of soil degradation in deforested areas of the humid tropics (Crasswell, 1989; Willet, 1994) and will be especially so in sloping areas such as those of S.E. Asia. Introducing simple practices can reduce erosion to acceptable levels for the long term. Comia *et al.* (1994) introduced various alley cropping (*Desmanthus virgatus*) practices to compare soil loss and nutrient loss with that of the traditional up and down slope cultivation. The introduction of hedgerows and alleys caused marked reductions in runoff and loss, with further reductions with crop residue and hedgerow pruning mulch and minimum tillage (see Table 5.3).

Table 5.3 Effects of alley cropping and mulching on runoff, soil and nutrient losses.
(source: Paningbatan, 1990; Willet, 1994; and Comia et al., 1994)

	Farmers' practice	1. Alley cropping only	2. Alley cropping + mulch	3. Alleys + mulch + minimum tillage
1989 Runoff (mm)	347	184	75	32
1989 Soil loss (t ha^{-1})	124	41	3	0.2
1990 Runoff (mm)	586	342	162	253
1990 Soil loss (t ha^{-1})	198	25	5	5
1990 OM loss (kg ha^{-1})	5916	946	224	275
1990 total N loss (kg ha^{-1})	296	47	11	14
1990 P loss (kg ha^{-1})	2.5	0.4	0.1	0.1
1990 K loss (kg ha^{-1})	266	34	9	4

Reduced losses were ascribed to:

- Reduced runoff - hedges reducing runoff velocity thus allowing deposition.
- Mulch reducing raindrop detachment, and particle entrainment by overland flow.

Maize yields were actually higher in the alley system, although the area occupied by *Desmanthus* hedges reduced the area maize yields to that of sole maize. Yields of intercropped mung bean were lower than those of sole mung bean.

From the same experiment, Comia *et al.* (1994) calculated the loss of organic matter and nutrients (see table 5.3) and found OM, N, P and K losses were at least 6, 26 and 21 times greater under traditional farmer practice than alley cropping treatments 1, 2 and 3.

Results from the implementation of these soil conservation measures compared to current practice suggest soil fertility will not decline as rapidly so that in the long term yields will exceed farmers' practice. Unfortunately, there is a financial disincentive to farmers adopting the alley conservation system because the benefits are long-term and the farmer is often influenced by his short-term returns (Willet, 1994)

It should be recognised that the two beneficial processes above depend upon the type of management system transfer of leaf litter off-site can undermine these processes in managed tree zones such as the miombo woodlands (Nyathi and Campbell, 1993). Trees only provide such 'services' when fully established with a substantial litter layer (Sanchez *et al.*, 1985). Sequential agroforestry systems that include crops or ground cover during the establishment phase can reduce this limitation.

Improvements in the structural properties of soils rely, in part, on the perennial nature of tree root systems in contrast to the 'temporary' nature of annual cropping systems. These perennial roots provide an important, dependable and continual source of C substrate to micro-organism communities, who in turn produce microbial mucilage that may bind soil particles into stable aggregates improving soil structure (Tisdall and Oades, 1982).

Gaseous losses (volatilization and burn losses)

Gaseous losses from managed or natural tropical systems are poorly quantified. Denitrification is likely to be important in agroforestry systems that maintain a thick, long-lasting mulch layer, especially in humid areas such as Amazonia (Keller *et al.*, 1986; Salati *et al.*, 1982), and Humid West Africa (Robertson and Rosswall, 1986). NH_3 can also be lost from plant leaves and animal excreta (Woodmansee, 1978) with the latter an important process in agrosilvopastoral systems.

Some improved fallow practices involve burning residue. The nature and magnitude of the losses are very similar to those recorded for slash and burn practices(see above). Mulongoy *et al.* (pers. comm. c.f. Swift *et al.*, 1994) investigated N losses by ammonia volatilization in pot experiments of an Alfisol soil (pH 6.2). Losses were significant from the soil alone, but were larger when amended with *Leucaena* or *Cassia* prunings. C / N and lignin / N ratios appeared to be important controls of ammonia release suggesting a link between mineralization and volatilization. These potentially significant losses are, as yet, unrecorded in the field (Swift et al., 1994).

Denitrification

As with measures of volatilisation, the evidence available is only from laboratory studies. Ayanaba and Veldkamp (1980) found significant emissions of N_2O and N_2 from laboratory incubated soils taken along a toposequence of rice cultivation; the highest activity was recorded in those soils subjected to periodic wetting and drying. The presence of readily decomposable C compounds in systems such as alley cropping could promote heterotrophic denitrification (Swift *et al.*, 1994)

Harvest Losses

In managed agroforestry systems, nutrients are principally removed as harvested products (Szott *et al.*, 1991). Low-input systems, such as most agroforestry systems, operate as long as there are only low harvest outputs. Removing nutrients in harvest depletes available stocks and may induce nutrient deficiencies in plants. Even in the absence of leaching losses, export of products from the field will lead to nutrient depletion. Reductions in yields as a result of these losses may not occur for many years in fertile soils. The response in infertile soils, such as Oxisols and Ultisols, may become apparent very rapidly with marked yield declines (Sanchez and Benites, 1987).

Phosphorus appears as the critical harvested nutrient in many crop systems and soils (Sanchez and Benites, 1987). Reynolds (1994) reviewing alley cropping, stated that P offtake in crop harvests are around 10 times larger than that in any other outflow. Van der Heide *et al.* (1992) assessing the viability of low-input cropping on acid soils in the humid tropics stated that the low supply of P and K in such soils means that to maintain harvest output there is no alternative to using fertilizers to compensate for product removal. Howeler (1991) provided estimates of the nutrient content of the total above ground biomass and marketable products (Table 5.4).

Table 5.4 Nutrient content (kg ha^{-1}) in above-ground biomass and marketable products for 5 food crops at 'target' yields (Based on Howeler, 1991)

	Yield	Above-ground biomass			Marketable products		
Crop	**Mg ha^{-1}**	N	**P**	**K**	N	**P**	**K**
Cassava - tuber	25	112	17	159	34	6	91
Upland rice - grain	2.5	50	9	76	29	6	5
Maize - grain	5	148	14	194	80	9	16
Soyabean - grain	1.5	129	12	43	112	11	59
Cowpea - grain	2.0	80	7	58	67	6	30

Fodder removal from the tree components will also result in a net loss from the system (even if manures are returned). Lulandala and Hall (1990) studied nutrient removal for *Leucaena* hedgerows in monoculture and intercropped systems with fertilized crops. Overall nutrient losses (kg ha^{-1} yr^{-1}) of 88 N, 48 K, 20 Ca, 8 Mg and 5 P were estimated. The losses of N and K were considered particularly high. If vegetative material is removed for fodder the losses are greater and even higher levels of fertilizer application (particularly for N) are required. Lulandala and Hall noted that these losses might be balanced by N-fixation estimated at 200 kg ha^{-1} yr^{-1}. Comparing systems where fodder removal was a component of the agroforestry system Lulandala and Hall reported available P, and exchangeable K were 23.7 ppm and 0.57 cmol$_c$ kg^{-1} after 33 months of intercropped beans, compared to 31.4 P ppm and 0.67 K cmol$_c$ kg^{-1} under monocropped beans. Under these circumstances it might be considered that a *Leucaena* 'nutrient mining' situation arises, the rate of degradation dependent on edaphic, climatic circumstances and intensity of cropping (Lulandala and Hall, 1990). Replacement costs for these 'exported' nutrients would be extremely high, so an alternative system of fodder production in conjunction with the cut and carry system of livestock rearing is desirable (Lulandala, 1995).

5.4.2 Nutrient inputs

Nutrient additions to the system

When discussing nutrient balances it is necessary to make an important distinction between:

a. nutrients simply being recycled within the system.
b. nutrients being added to the system, through the action of the trees.

Prunings, litterfall and cut fallows recycle nutrients within the soil-plant system. These are **not** nutrient additions to the system. Nutrient additions occur through:

i. enhanced atmospheric deposition.
ii. N fixation.
iii. mycorrhizal association.
iv. deep nutrient uptake / capture.
v. external inorganic inputs.

Atmospheric Deposition

Atmospheric deposition of nutrients is usually small in magnitude (Nortcliff, 1995) but may have importance over a long time period. Nutrient inputs from precipitation are little affected by soil type, or agroforestry system. Tree crowns however act as dust traps and this may explain the observed higher clay contents associated higher organic matter levels, and general enhanced nutrient levels beneath tree canopies such as *Acacia albida* (Sanchez, 1987; Kellman, 1979,). Sulphur concentration increases under *A. albida*, may be explained by foliage capture of atmospheric SO_2 in the dry season, when savanna vegetation and crop residues are burnt (Weil and Mughoghio, 1993). These inputs to the system are potentially significant in silvopastoral systems, fallows and other systems involving a large canopy surface area, but negligible in reduced canopy systems such as alley cropping (Szott *et al.*, 1991)

Nitrogen Fixation

The use of N-fixing woody legumes in agroforestry systems can increase nitrogen inputs (Dommergues, 1987) through their ability to fix atmospheric nitrogen and contribute to soil reserves through leaf litter and the turnover decomposition of root debris and nodules. Biological nitrogen fixation takes place through symbiotic means, exhibited by *Leguminousae* and *Ulmaceae* tree families, in association with nodulating micro-organisms of the genus *Rhizobium* and *Bradyrhizobium*, and by some non-leguminous trees (actinomycetes) in association with *Frankia* (Brewbaker *et al.*, 1990).

In natural ecosystems and improved pasture systems, non-symbiotic fixation by free-living N-fixing bacteria and cyanobacteria (blue-green algae) can be a significant factor but is thought to be of minor importance in agricultural systems (Giller and Wilson, 1991)

A large number of N fixing trees (NFTs) have been identified amounting to about 650 tree and large shrub species belonging to 9 families (Brewbaker *et al.* 1990). A smaller number have been identified that are included in various farming systems (Nair, 1989).

Leaves and roots of NFTs generally have a lower C : N ratio than most other species, and normally leaf size is small. These attributes lead to quick decomposition of tree residue inputs to the soil system.

There are few direct measurements of the magnitude of biological N fixation in tropical trees because the 3 methods a) acetylene reduction, b) nitrogen difference, and c) 15N labelling, are difficult to use (Dommergues, 1987). Table 5.5 provides examples of the N fixing potential of various species suitable for agroforestry systems.

Unfortunately, at present it is impossible to assess the contribution of N-fixing trees to the N cycle in agroforestry systems because measurement are few and commonly only estimate the proportions of N from N-fixation. Few estimates assess total amount of N fixed. An exception is a study by Sanginga *et al.*, (1986) who showed that between 224 and 274 kg N ha^{-1} were fixed in prunings of *Leucaena leucocephala* hedgerows inoculated with *Rhizobium* compared to un-inoculated *L. leucocephala* hedgerows dependent on the soil for N growth. However, to improve the accuracy, total N measurements should also include the trunk and below ground inputs; this is a formidable task (Giller *et al.*, 1994).

Table 5.5 Estimates of N2-fixation amounts in legume trees and shrubs in the tropics
(Source: Giller and Wilson, 1991)

Species	% N fixed	kg N fixed ha^{-1}
Acacia spp.	52-66	-
Calliandra calothyrsus	0-14	-
Desmodium rensoni	68-84	-
Gliricidia sepium	26-75	-
Leucaena leucocephala	34-100	76-274
Paraserianthes falcataria	55	-
Sesbania spp.	78-100	83-109

Constraints to Nitrogen Fixation

Nitrogen contribution of NFTs varies greatly depending upon: soil, climate, species and management.

Soil / Climatic constraints

The soil conditions influencing nodulation and N fixation are:

1) Temperature - In soils exposed to direct insolation in the tropics temperatures can reach 65 - 70°C at the soil surface, and 50°C 5 cm below (Dudeja and Khurana, 1989). This is sufficient to kill many bacteria. High temperatures can prevent nodulation or inhibit nodule N-fixation in legumes (Day *et al.*, 1978). Nodulation and fixation will not be efficient above 35°C (Daniel, 1994).

2) Moisture - Rhizobia numbers decline as soil dries with Bradyrhizobium strains being the more tolerant. Rates of N-fixation in legumes are more sensitive to soil moisture content than other processes such as photosynthesis, transpiration, or leaf growth rates

(Sinclair *et al.*, 1987). Tolerance to drought is strongly influenced by the plant's ability to capture water, i.e. the extent of the root system. Deans *et al.* (IITA 1994) found that the abundance of the rhizobial population mirrored that of the root system to a depth of 30m under *A. senegal.* NFTs with deep root systems and active rhizobial nodules recorded below 2 m can continue to fix N even in drought (Sanginga *et al.*. 1994).

3) Salinity - Occurs in hot semi-arid and arid environments due to accumulation of salts in the topsoil (Nortcliff ,1988). Saline stress is more permanent than periodic drought, therefore micro-organisms must not only survive but grow (Sprent, 1984). Tree tolerance is generally more important than the tolerance of the rhizobia (Craig *et al.*, 1991).

4) Acidity - The problem of low pH itself, the associated increase in available Al, Fe and Mn, and the associated deficiency of available P, Mo and Ca, in acidic Oxisols, Ultisols and some Inceptisols will limit N fixation (Daniel, 1994).

Rhizobia tolerant to low acidity generally have a lower N-fixing potential (Halliday, 1981), but are not necessarily tolerant to Al toxicity (Keyser and Munns, 1979).

5) P status - N fixation requires energy supplied by the host tree, which requires P. Therefore symbiosis is less productive in P deficient soil (Daniel, 1994). Genotype differences in *L. leucocephala* and *G. sepium* in the ability to grow in P deficient soil (Sanginga *et al.*, 1991a) could be exploited to maximise N fixation. Field resnlts have shown P uptake relates strongly to root length and size in early establishing growth. P translocation and use efficiency possibly becoming more important with age (Sanginga *et al.*, 1994). Mycorrhizal association should be advantageous in such situations. P requirements need to be taken into account in plant selection and breeding strategies. An increase in nodule biomass and function in *Inga jinicuil* correlated with increasing P applications to coffee agroforestry systems (Young ,1987).

6) N status - Sanginga *et al.* (1988) demonstrated a 50% derease in fixation with *L. leucocephala* when 40 kg N ha^{-1} wasapplied to an Alfisol in Nigeria. Rhizobial symbiotic relationships are less efficient in soils that are not N limiting as the symbiont N can be replaced by soil sources (Daniel, 1994).

This final statement raises the question of the long term effectiveness of symbiotic associations, as they commonly become less effective once N fertility is improved (Daniel, 1994). To assess long-term sustainability of agroforestry systems analysis of N input changes with tree age and agroforestry system age are required (Giller *et al.*, 1994). The proportion of plant N derived from the atmosphere is strongly influenced by age. Sanginga and Mnlongoy (1994) showed that by 9 months of age there is little difference between provenances that had shown marked variation when younger. Furthermore, estimates of the proportion of plant N derived from the atmosphere under field conditions are lower than those from pot trials. There is a clear need for field research over longer periods of time. This is further substantiated as some tree species (e.g. *Erythrina* spp. in Sumatra and Indonesia, and *Sesbania sesban* in Rwanda) die out rapidly after 4 to 5 years annual coppicing management.(Giller *et al.*, 1994)

Species

Dommergues (1987) categorised NFTs in 2 groups based on thier N-fixing ability. High potential (e.g. *L. leucocephala, Acacia mangium)* fixing more than 100 kg ha^{-1} yr^{-1} and low potential (e.g. *Acacia senegal, A. (Faidherbia) albid)*, < 20 kg ha^{-1} yr^{-1}. Other agroforestry tree species such as *Senna siamea* and *Senna spectabilis* do not nodulate.

Estimates of N fixed by NFTs vary widely (see Table 5.4). For *Leucaena leucocephala*, a well investigated species, rates ranged from 100 to 300 kg ha^{-1} yr^{-1} (Danso *et al.*., 1992), which broadly matches the rates proposed by Giller and Wilson (1991). The success of N fixation also depends on the presence of suitable Rhizobia; some are promiscuous, others very specific. There is some specificity between NFTs and nodulating strain (Danso *et al.*, 1992). Suitable strains of Rhizobia for specific situations (soil type and tree species) have been identified (Mulongoy *et al.*, 1992). The general performance of an NFT is influenced by the effectiveness of its associated Rhizobia. Within one tree provenance of *Gliricidia sepium*, the amount of N fixed varied greatly depending upon the Rhizobium. Between 20 mg per plant and 129 mg over 14 weeks growth (36% to 71% of total plant N Sanginga *et al.*, 1991b).

Constraints to N-fixation may arise simply through the nature of the symbiotic relationship itself; the effects of regulation of assimilate partitioning, long distance transport and nutrition of the component organs being relatively unknown (Atkins, 1986).

Management

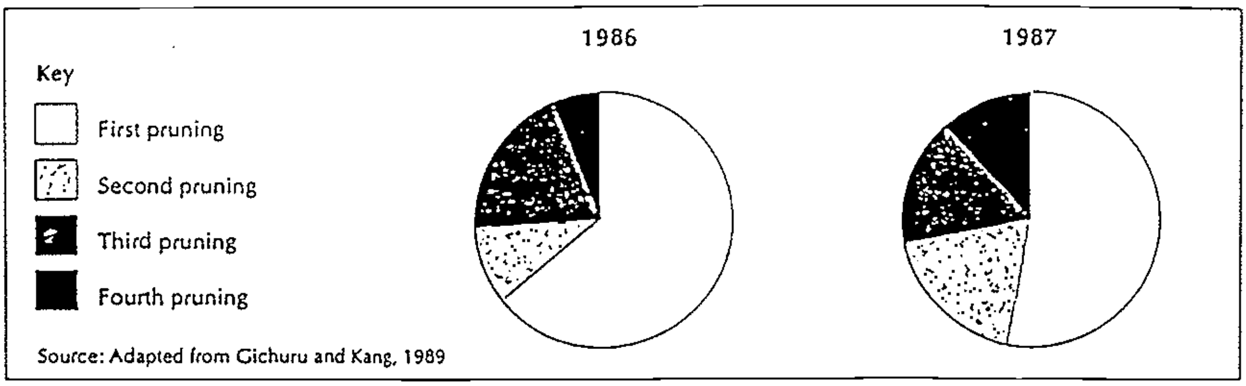
Pruning has been shown to reduce apical dominance of the root system, leading to short, but well branched systems (Hairiah *et al.*, 1992) as well as reducing the N fixation capacity. In *Leucaena leucocephala*, cutting management resulted in nodule senescence and decay within 3 weeks following each cut. Few nodules regrew unassisted and response to re-inoculation was tree genotype dependent (Sanginga *et al.*, 1990). Young leucaena and sesbania grown in pots senesced 30% and 95% of their living nodule biomass, respectively, when pruned (Fownes and Anderson, 1991). After pruning there is an observed associated lag phase, involving low above-ground dry matter production and suppressed root growth and N fixation (Gueverra *et al.*, 1978).

Sanginga *et al.* (1990) measured the partitioning of 15N after three successive cuttings of *L. leucocephala*. About 60% of the total N fixed remained in the roots with only 20% partitioned to the shoots. N reserves in roots and nodules must be considered when estimating fixed N_2 or N balances after pruning or cutting. Nitrogen rich roots of NFTs can be expected to transfer considerable amounts of N when they decay (Sprent, 1983). Sanginga *et al.* (1992) emphasise the need to include root N when estimating the contribution of atmospheric N. L. *leucocephala* roots were reported to provide 32 kg N ha^{-1} which was half the total N contribution of a sequential cropping system (Sanginga *et al.*, 1988).

Kang and Mulongoy (1992) concluded that N yield of prunings is highly correlated with pruning biomass yield. A number of management factors affect the N yield of prunings (Fig. 5.3):

1) Height and frequency of pruning, low pruning height and high pruning frequency giving lower yields (Duguma *et al.*, 1988).
2) Plant density and inter-hedgerow spacing (Kang *et al.*1990). .
3) Timing of pruning during the cropping season. Over half a season's N yield is realised at the first pruning, following the dry season (Gichuru and Kang, 1989).

Fig. 5.3 Nitrogen yield of prunings of *Calliandra calothyrsus* during the cropping season



Source: Adapted from Gichuru and Kang, 1989

In a comparative study of 3 tree legumes for alley cropping (Table 5.6), the amounts of N, P and K in initial (2 years after planting) and subsequent prunings (6, 22 and 30 weeks later) were compared (Yamoah *et al.*, 1986)

Table 5.6 Nutrient content of prunings from 3 tree legumes in alley cropping experiments at Ibadan, Nigeria. Tree spacing 0.5m, alley width 4m.(Source: Yamoah *et al.*, 1986)

	Nutrient	Nutrient content in prunings (kg ha^{-1})			
		1st cutting	2nd cutting	3rd cutting	4th cutting
Gliricidia sepium	N	126	119	144	88
	P	8	7	9	5
	K	86	75	12	52
Flemingia macrophylla	N	62	46	25	23
	P	6	5	3	3
	K	40	35	16	23
Senna siamea	N	274	16	78	5
	P	27	2	10	1
	K	123	12	59	5

(Note 1st cutting includes litterfall during pre-2 year growth)

Summarising the table:

1. *Senna siamea's* (non-N fixer) initial N contribution was greatest, decreasing dramatically afterwards.
2. Gliricidia maintained substantially greater N nutrient contents.
3. P concentrations in all but *Gliricidia* showed considerable decline.

4. Decomposition of *Gliricidia* prunings was fastest.
5. *Flemingia* was initially smallest but became larger in subsequent cuttings.
6. *Senna* was consistently slow to decompose, benefiting weed suppression.

In general more frequent pruning results in higher % N in the biomass, but less biomass production (Giller & Wilson, 1991).

As root systems are not apatially uniform in many simultaneous agroforestry systems, neither are the benefits of root decay. The use of prunings as green manure or mulch to increase fertility has not been advocated in alley cropping systems (Kang *et al.*, 1981, Yamoah *et al.*, 1986).

Host / Rhizobium Combination Selection

Selection of host plants and symbiotic micro-organisms should be based upon tolerance to site dependent constraints, such as soil acidity (Hutton, 1983), and / or deficiencies of nutrient such as P and Ca (Szott *et al.*, 1991). Field trials of 12 Central American provenances of *Gliricidia sepium* on an Ultisol (pH 4.5, Al saturation 65 - 85%) at Yurimaguas, Peru, produced large differences in growth rates and biomass production among provenances. Production by a Guatemalan provenance exceeded that of the local varieties (Fernandes, 1990). Selection should also account for N-fixing abilities and effectiveness over time, and the effect of management practice eg. pruning (Daniel, 1994).

Current quantitative information appears inadequate, Avery (1991) concluded that the agroforestry literature on N fixation was inconclusive and conflicting, and descriptive rather than quantitative. Because the total contribution of NFTs is not available and limiting factors are so varied that extrapolation from research station data, (commonly under optimal conditions), is precarious, it is widely recognised that specific recommendations of NFTs for agroforestry systems cannot yet be made. Nevertheless, the evidence in support of the many benefits of NFT inclusion in agroforestry systems appears undeniable.

Non-symbiotic N fixation

Free-living N fixing bacteria are heterotrophic and therefore dependent upon organic C for energy. An increase in organic C input, a remit for agroforestry systems, can create a favourable environment for bacterial growth and has been suggested as an explanation for N increases around non-N fixing plants such as Neem (Radwanski and Wickens, 1981). Jung (1967) concluded that although N fixation is possible in *A. albida*, it is not essential because these trees create a good nitrogen regime through normal microbial processes. In a semi-arid, natural ecosystem Felker *et al.* (1980) concluded that all the non-legume sources combined, contribute no more than 4 kg N ha^{-1} yr^{-1}. For tropical cropping systems free-living bacteria undoubtedly fix N_2 in soil, and are stimulated by organic matter addition. Estimates for amounts contributed in the field are poor, though unlikely to exceed 5 kg N ha^{-1} yr^{-1}(Giller & Wilson, 1991).

Garcia-Moya and McKell (1970) found no difference between legumes and non-legumes in the amount of vegetation or soil nitrogen, in a desert wash community. They concluded that the shrubs were more important as a reservoir for N rather than N fixation.

Deep nutrient capture

The nutrient pumping hypothesis states that trees with deep rooting systems may absorb nutrients from the subsoil and deposit them in or on the surface soil via above- and below-ground litter production, leaching from foliage, pruning of leaves or branches, or indirectly through deposition of manure from livestock that browse on such trees (Nair, 1984, Young, 1989b). Translocation of nutrients from depth to superficial soil horizons can thus introduce additional nutrients to the agroforestry cycle and improve the overall productivity system. The ability of a tree to absorb nutrients from outside the soil volume exploited by the crop roots depends upon the spatial distribution of roots and temporal patterns of root growth. At any given tree age, the spatial distribution of roots can vary with provenance (Vandenbelt, 1991) and species (Ruhigwa *et al.*, 1993). In the absence of soil restriction, many tree species have the potential to develop roots extending into the deep subsoil and to take up nutrients (Jenik, 1978; Stone and Kalisz, 1991; Comerford *et al.*, 1984). Improved agroforestry systems should attempt to select species to exploit the maximum soil volume, whilst minimising competition (Anderson and Sinclair, 1993). Desirable root architecture for trees differs between sequential and simultaneous agroforestry systems (Van Noordwijk and Purnomosidhi, 1995), the latter demanding complementary rooting patterns to the crop to reduce competition, and the former requiring an extensive rooting system to enhance nutrient capture and transfer. Selection based on adaption to soil chemical and physical constraints may be important in specific situations. Roots that are able to penetrate subsoils with high aluminium saturation and low available nutrients create root channels that subsequent crops can then follow as well as aiding aeration and water movement (van Noordwijk *et al.*. 1991).

The actual contribution of this deep uptake process to nutrient cycling in agroforestry systems is not known (Schroth 1995). Evidence from agroforestry and natural ecosystems suggest that the majority of tree roots are found in the topsoil and that the contribution of subsoil zones increases as the soil dries. Therefore nutrient pumping is less likely in more humid climates (Grubb, 1989; Van Noordwijk, 1989; Schroth, 1995). Data on the rooting depths for agroforestry species are few and restricted to relatively young trees. Such data are relevant in sequential agroforestry systems such as improved fallows. Jonnson *et al.* (1988) studied 5 tree species used in alley farming in Tanzania and found similar root distributions in each but double the root density of maize.

In assessing the role of deep roots, a differentiation must be made between 'capture' of nutrients that are leached down to the subsoil ('safety net' effect), and nutrients that are weathered in the subsoil ('deep mining' effect).

Weathered product uptake

In the consideration of nutrient dynamics it is important to consider the role of pedogenic and geologic processes which result from weathering of primary and secondary soil minerals, or changes in non- or slowly-available to readily available forms. These processes are controlled by soil type, inorganic chemical processes, temperature and rainfall, and as a consequence the variations are greater with respect to soil type than the type of agroforestry system. As discussed for natural tropical forests, these processes will be significant on more fertile soils where external (open) cycling occurs.

The magnitude and importance of the uptake of freshly weathered products, P, K, other bases and micronutrients from depth, is still to be fully quantified. Evidence from natural systems of high concentrations of nutrients in forest topsoils compared to subsoil under trees such as *Faidherbia albida,* has been suggested as possible support for this mechanism. Subsoil concentrations of P, Ca and Mg are greatly dependent on the type, degree of weathering, and depth to the parent material. The potential for deep nutrient uptake in acid, infertile soils may be limited by chemical barriers to root penetration, such as high aluminium saturation and low levels of P and exchangeable bases in the subsoil, and by lack of weatherable minerals in the subsoil (Szott *et al.*, 1991).

For semi-arid regions the subsoil nutrient concentrations of P and bases available for root uptake are very low (Kellman ,1979; Grubb, 1989) and there is no evidence of good relationships between P yield in the herbage / crop biomass and that of the woody plant as would be expected if deep nutrient uptake was a major component of the nutrient cycling system. However this lack of a good relationship might be explained by more efficient tree root competition (Breman and Kessler, 1995).

Subsoil nitrates

High nitrate and K concentrations are frequently found in the subsoil, due to leaching. Nitrate that is leached down the soil profile can be adsorbed on positively charged surfaces (Cahn *et al.*, 1992). This sorption can retard the downward movement of NO_3 resulting in an accumulation at depth (Wong *et al.*, 1987). Considerable subsoil concentration have been recorded in certain situations. An average of 2200 kg NO_3-N ha^{-1} was detected at 1-5 m depth under fertilized coffee, associated with a band of soil with high positive charge (Michori ,1993).

In an investigation of unfertilized N-fixing trees in Senegal, Deans *et al.* (IITA 1994) discovered a layer at 15 to 22m depth containing a nitrate soil solution approaching 180 mg l^{-1} (Fig. 5.4). Microbial Rhizobium populations beneath *A. Senegal* were closely associated with the distribution of fine roots being common to the surface, infrequent from 7m to 30m, and with increased frequency closer to the water table (see moisture constraints to N-fixation below). Beneath *Faidherbia albida* nitrate concentrations reached 230 mg l^{-1} in a layer extending from 4 to 10 m in depth. These results suggest that the losses may be associated with the presence of N-fixing plants, but this has to confirmed.

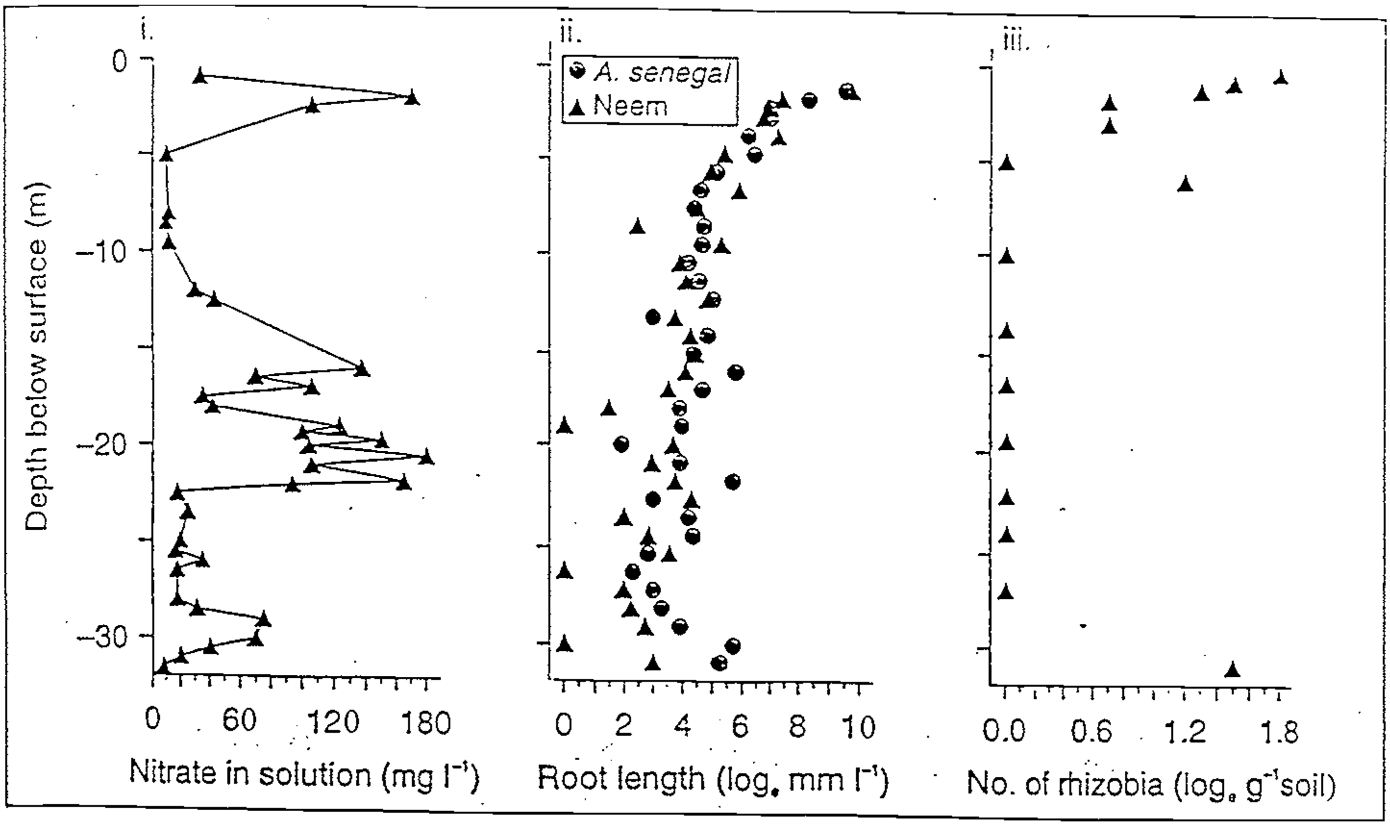


Fig 5.4 Distributions of (i) nitrate in solution beneath an *Acacia senegal* tree, (ii) fine root length of *A. senegal* and neem, and (iii) nitrogen-fixing rhizobia, between the soil surface and the water table at Ndiery in Senegal

Research in the subhumid highlands of Kenya on two N deficient Nitisols (red Alfisols and Oxisols with high iron content) discovered nitrate in the order of 120 kg N ha^{-1} at 50 - 200 cm depth (Hartemink *et al.*, in press). The source of this subsoil reserve was believed to be from the mineralization of topsoil organic nitrogen which subsequently leached, particularly at the start of the rainy season when nutrient conserving mechanisms of agroforestry trees are particularly relevant because crop root systems are absent or insufficiently developed to 'capture' these nutrients (Schroth, 1995). Hartemink *et al.* (in press) hypothesized that tree integration could reduce NO_3 leaching and increase subsoil N utilization. Both sesbania and weed fallows showed reductions in the subsoil nitrate pool. The seasonal decreases in subsoil NO_3-N levels were 22 kg N ha^{-1} from the sesbania fallow, and 26 kg N ha^{-1} for a weed fallow, between planting and harvesting. Maize grown alone did not cause a net decrease in subsoil nitrate. The reduction beneath sesbania and weeds presumably resulted from deeper rooting and greater uptake of nitrate. The sesbania tree in effect expands the volume of soil explored by the system (Cahn *et al.*, 1992).

There is further evidence of reduced nutrient leaching losses from agroforestry systems (Kuhne, 1993) and reductions in the subsoil nutrient content have been used as evidence of deep nutrient uptake in tropical plantations (Sanchez *et al.*, 1985) and perennial cropping systems (Seyfried and Rao, 1991).

These data must be interpreted with caution, since nutrient leaching or organic matter deposition may influence subsoil nutrient dynamics (Szott *et al.*, 1991). The greatest potential for nutrient pumping in agroforestry systems exists with long-lived perennial crops on relatively fertile sites where physical and chemical barriers are absent, subsoil nutrient concentrations are high, and undisturbed below-ground growth over relatively long periods allows greater exploration of the subsoil (Szott pers. comm.).

Mycorrhizal association

Mycorrhizae are symbiotic associations between soil fungi and plant roots. The beneficial effects of increased water and nutrient uptake, enhanced N fixation and improved resistance to pathogens were briefly considered in the review of natural tropical forest systems.

Phosphorus

Increased uptake of P is often cited to highlight the potential importance of mycorrhizae in low nutrient tropical systems. Vesicular-Arbuscular Mycorrhizae (VAM), the most common in tropical agroecosystems, are of particular significance in acid tropical soils where P availability is low, and a capacity to scavenge P is most critical. Mycorrhizae achieve this by increasing the absorptive area through fungal structures (hyphae), and may also increase P solubility through siderophore phosphatase production (Harley and Smith, 1984). Osunubi *et al.* (1991) showed that mycorrhizal inoculated seedlings of tree species used in alley cropping accumulated more biomass, P and N than uninoculated trees.

Increased P uptake by host plants via mycorrhizae has been shown to be associated with improved growth and N fixation in annual and tree legume species (Barae and Azcon-Aguilar, 1983; Huang *et al.*, 1985). Mycorrhizae association increased N fixation by rhizobium in *L. leucocephala* (Purcino et al., 1986), and by Frankia in Casuarinas (Reddell *et al.*, 1986).

The high P requirement for leguminous N fixation, and a minimum level of soil P for adequate mycorrhizal functioning, suggests that nitrogen fixation is likely to be limited in some acid , infertile soils low in available P (Szott *et al.,* 1991). However, some ectomycorrhizal species may be able to tolerate much lower levels of available soil P than endomycorrhizal species (Hogberg, 1986) and allow their host to maintain high internal P concentrations. For example, *Cassia reticulata*, a non-nodulating legume used in alley cropping at Yurimaguas, has a higher foliar N content than nodulated legumes such as *Inga edulis* and *Gliricidia sepium* (Salazar, unpublished cited by Szott *et al.,* 1991). There is obviously a need for further investigations into the roles of VAM and ectomycorrhizae.

Inoculation of both N fixing rhizobium and mycorrhizae has been shown to lead to significant increases in dry matter production particularly in P deficient soils (De la Cruz *et al.*, 1988). Majunath *et al.* (1984) inoculated *L. leucocephala* with an efficient mycorrhizal species (*Glomus fasciculatum*) and an effective Rhizobium resulting in improved P uptake, rhizobial infection, nodule N content, N fixation and dry weight, compared to uninoculated trees. Inoculation of just the mycorrhizal fungi also significantly improved nodulation by native rhizobium. The synergistic interaction of the two symbionts is an important target for research (*Swift et al.*, 1994).

Besides P, mycorrhizae also aid in absorption of Zn, Cu and Mo (Gilmour, 1971; Bowen,1984). Of perhaps greater significance is the capacity to enhance water uptake, and drought tolerance (Michelsen and Rosendahl, 1990; Osunubi *et al.*, 1991; Awotoye *et al.*, 1992). This could extend the application range of several tree species.

5.4.3 Nutrient Cycling

An advantage commonly attributed to agroforestry technologies is the potential for soil fertility improvement via more efficient cycling of nutrients (Nair, 1984) irrespective of nutrient additions to the system. This is achieved through the maintenance of a relatively closed nutrient cycle (Ingram, 1990). The hypothesis that agroforestry systems can lead to more closed nutrient cycling and to more efficient use of nutrients and less leaching loss has not been quantitatively proven although it is highly probable in certain systems (Sanchez, 1995).

Nutrient cycling processes are particularly relevant to agroforestry systems because tree components can have a similar effect to those of a natural system. The extent to which the system is closed will depend on factors that determine the nutrient losses and the amount of nutrients returned to the soil in residues (Ingram, 1990).

A fundamental principle of agroforestry system sustainability (or any system) is therefore the capacity to return to the soil, or replenish in other ways, the nutrients removed from it through harvests, runoff, erosion, leaching, denitrification and other loss pathways (Sanchez, 1995).

Mineralization of nutrients from organic forms

One of the important functions of organic inputs into the soil system is to supply nutrients to the crop. The quantity of nutrients added via organic inputs depends on first, the mass of organic inputs, and second, the concentration of nutrients in the tissue. Both of these vary with soil properties climate and production system.

Organic inputs to the soil must be considered separately to the SOM to understand properly the physical, chemical and biological processes involved in the sustainability of tropical agroforestry systems (Sanchez *et al.*, 1989).

Mass of organic inputs

1) Above-ground litter inputs

With regard to soil type, quantities of dry matter and nutrients recycled by the above-ground litter in agroforestry systems show the same general tendency as in natural forests described by Vitousek (1984), and illustrated by Furch and Klinge (1989) in Table 3.1. Litter production and the return of N, P, Ca and Mg in litter are larger on more fertile soils.

A large number of biomass production trials has been conducted in a range of climate and soil environments with a wide variety of leguminous and some non-leguminous trees. There is considerable variation in data, because of site characteristics, management, practices, method of sampling etc. (Table 5.7).

Table 5.7 Dry matter and nutrient inputs via litterfall / prunings in various production systems in the humid tropics. (Source: Szott *et al.*, 1991)

Systems	Dry matter t ha^{-1} yr^{-1}	N input kg ha^{-1} yr^{-1}	P input kg ha^{-1} yr^{-1}	K input kg ha^{-1} yr^{-1}	Ca input kg ha^{-1} yr^{-1}	Mg in kg ha
FERTILE SOILS						
Rainforest	10.5	162	9	41	171	37
High input cultivation*	9.3	139	15	98	52	23
Alley cropping						
L. leucocephala*	22.0	200-280	-	-	-	-
Gliricidia sepium*	11.0	171-205	-	-	-	-
Sesbania*	7.5	25-110	-	-	-	-
L.leucocephala	5-6.5	160	15	150	40	15
Erythrina poeppigiana*	9.6	278	24	216	120	52
Gliricidia sepium*	12.3	358	28	232	144	60
L.leucocephala	8.1	276	23	122	126	31
Erythrina spp.	8.1	198	25	147	111	26
Shade systems						
Coffee/Erythrina	17.2 (13.5)	366(182)	30(21)	264(156)	243(131)	48(27
Coffee/Erythrina/Cordia	15.8(9.1)	331(75)	22(8)	162(45)	328(46)	69(12
Coffee/Erythrina pruned*	20.0(12.2)	461(286)	35(24)	259(184)	243(121)	76(43)
Coffee/Erythrina not pruned*	7.6(2.0)	175(55)	11(4)	75(14)	122(40)	33(9)
Cacao/Erythrina*	6.5(2.5)	116(62)	6(4)	40(13)	116(47)	41(12)
Cacao/Cordia*	5.8(2.9)	95(60)	11(8)	57(33)	108(58)	43(23
Cacao/mixed shade	8.4	52	4	38	89	26
Cacao/Eryjthrina*	6.0	81	14	17	142	42

Systems	Dry matter t ha^{-1} yr^{-1}	N input kg kg ha^{-1} yr^{-1}	P input kg ha^{-1} yr^{-1}	K input kg ha^{-1} yr^{-1}	Ca input kg ha^{-1} yr^{-1}	Mg input kg ha^{-1}
INFERTILE SOILS						
Rainforest (Ox. / Ult.)	8.8	108	3	22	53	17
Rainforest (Spodosol)	7.4	48	2	22	63	10
Savanna (Oxisol)	3.5	25	5	31	10	11
Low input cultivation (Ult.)	6.0	77	12	188	27	12
Alley cropping (Ultisol)						
Inga edulis	5.6	136	10	52	31	8
Erythrina spp.	1.9	34	4	19	8	4
Inga edulis	12.5	-	-	-	-	-
Cassia reticulata	6.5	-	-	-	-	-
Gliricidia sepium	1.4	-	-	-	-	-
Shade systems						
Erythrina spp. (Dystropept)	11.8-18.4	170-238	14-24	119-138	84-222	27-5

* = Fertilized and limed; originally an acid, infertile soil.

Numbers in parentheses represent dry matter/ nutrient input production by Erythrina / Cordia.

For an understanding of potential alley cropping and multistrata agroforestry biomass production, in comparison with natural ecosystems and other agricultural systems see Table 5.8 below (Palm *et al.*, 1995).

In considering the amount of biomass required it is important to distinguish between the different tree components (litter, roots, wood, fruit), as several tree components may not be returned to the soil. As previously mentioned, agroforestry trees have production value that may outweigh their service value. There have been a large number of biomass screening trials, but recommendation for a tree species of sufficient biomass for a given environment and system is difficult as details of the climate, soil group and nutrient concentration are frequently absent. Also, comparison is undermined as different tree densities, pruning regimes and mulch components (leaves or wood and leaf components) are employed (Palm, 1995).

Table 5.8. Above-ground inputs in humid tropical forest and derived agricultural systems.

System	Above-ground inputs (dry matter t ha^{-1} yr^{-1})	Timing of inputs P = pulsed C = continuous	Quality of inputs (% lignin)
Natural forest - fertile soil	10.5	C	20 - 30
Natural forest - infertile soil	8.8	C	-
Shifting cultivation			
Cropping phase	3.2	P	< 8
Fallow phase - year 1	1.2	C	> 30
Fallow phase - year 5	4.8	-	-
Fallow phase - year 10	7.1	-	-
Fallow phase - year 20	9.7	-	-
Continuous cultivation			
Low input (rice-cowpea)	6.0	P	< 8
High input (maize-bean)	9.3	P	< 8
Agroforestry systems			
Alley cropping (prunings)	5 - 22	P	< 12
Multistrata system	6 - 20	-	-
Managed pasture	> 6.3	C	-

2) Roots as organic inputs

The importance of below ground litter in the recycling of dry matter and nutrients in agroforestry systems is virtually unknown. In natural ecosystems roots are known to be an important source of SOM and often play a dominant role in nutrient cycling (Fogel, 1980; Cuevas and Medina, 1986).

Root biomass - In contrast to above ground litter production root biomass is often larger on infertile soil than fertile soil (Szott *et al.*, 1991). Similarly, roots are proportionately more important in semi-arid areas (41-55% total biomass Garcia Moya and McKell, 1970), or moist savanna areas (35-40% Young, 1987), compared to humid tropical forests (about 15% Andriesse and Schelaas, 1987). Agroforestry systems may only have slightly greater root biomass than annual cropping systems (Szott *et al.*, 1991), although Ewel *et al.* (1982) comparing leaf and root biomass for 9 different land use systems in Costa Rica and Mexico, found agroforestry root biomass to be more than double that of the other agricultural systems (Table 5.9).

Table 5.9 Leaf and root biomass (kg ha^{-1}) in 9 land use systems (root biomass to 25 cm depth) from Ewel et al., 1982.

	Agricultural systems			Forestry systems		Agroforestry systems			
	Young maize	Mature maize	Sweet potato	Gmelina	Second forest	Coffee erythrina	Cacao cordia	Tree garden	Planted fallow
Leaf biomass	330	1000	1070	3120	3070	2720	2040	2450	2480
Root biomass	390	1150	410	1280	2170	2350	2720	3070	4220
Ratio	1.18	1.15	0.38	0.41	0.71	0.86	1.33	1.25	1.70

Sesbania sesban fallows at Chipata (ICRAF, 1995) were investigated for their above-ground foliar and below-ground root biomass (Table 5.10). Sesbania root biomass left in the soil was 4 - 6 times higher than the twig and foliar biomass added to the soil at the end of the fallow. Of the total biomass, roots accounted for 53% in 1 year fallow and 36% in 2 year fallow. Between 40 and 60 % of this root biomass was located in the top 25 cm of soil. The contribution of Sesbania roots to the fallow effect was not clearly quantified but the data suggest that root biomass is an important input to the system.

Table 5.10 Above-ground foliar and below-ground root biomass from 1 and 2 year Sesbania sesban fallows at Chipata, Zambia (ICRAF, 1995)

Component	1 year (1992)	2 year (1992)	1 year (1993)	2 year (1993)
Wood (t ha^{-1})	3.2	13.0	10.1	15.1
Litter fall (t ha^{-1})	0.96	3.05	1.36	4.00
Leaves + twigs(t ha^{-1})	0.18	0.35	0.5	0.5
Root biomass	1.31	1.71	2.13	2.93

Root turnover. Such estimates of inputs based on root biomass measured at crop harvest do not include C and nutrient inputs to the soil through root turnover, sloughing or exudation. Such inputs are much greater than standing root biomass would suggest (Bowen 1985). Exudates and exfoliates (more readily decomposable than root litter) can directly account for a high proportion of total C transfer below-ground (Milchunas *et al.*, 1985) and don't require microbial intervention.

Despite considerable research into the below-ground biomass and distribution for agroforestry trees (Jonnson *et al.*, 1988; Ruhwiga *et al.*, 1992), there is almost no available data on root turnover and the corresponding organic matter inputs.

One study by Schroth (1994) has attempted to quantify root turnover and the magnitude of organic inputs, through monitoring above- and below-ground biomass in sole cropping and alley cropping with *Gliricidia sepium*. Live root mass was higher in the alley cropping but total root production was little affected by hedgerow introduction, as root turnover was more rapid for sole cropping when perennial roots were absent. The conclusion was that root production in agroforestry and sole cropping were similar, and equally distributed in topsoil and subsoil, with 55% of

1100 kg/ha/yr produced in the 0-50 cm soil zone being present in the top 10 cm. It was estimated that less than 10% of the total biomass production was invested in fine root biomass in both cropping systems. It was acknowledged that this approach still ignores the unknown quantity of C release through sloughed tissues, mucilage, animal grazing or disease (Vogt *et al.*, 1991) and that the balancing transfer method for estimating turnover is open to errors.

An important factor influencing root turnover is pruning which leads to the decrease in hedgerow root biomass. Excessive pruning leads to a redirection of assimilates to above-ground biomass (Schroth and Zech, 1995). As pruning is an essential component in alley systems to minimise resource competition and recycle resources, there is probably more scope for maximising root C and nutrient inputs in less intimate tree-crop associations such as improved fallows. It should be noted that *Gliricidia sepium* is consistently a low root producer (Schroth, 1994; Rao *et al.*, 1993) more research is needed to investigate below-ground productive agroforestry trees. One such example estimated net primary production of fine roots, based on turnover, to be 102 kg N ha^{-1} (Smucker *et al.*, 1994, cited by Reynolds 1994). In this case it would appear that total root production is 10-15 times the standing fine root biomass but no information was given of the tree species involved.

Schroth (1994) produced unexpected soil fertility conservation in the *G. sepium* alley irrespective of whether mulch was applied or not. The low direct contribution of hedgerow roots does not suggest that the *Gliricidia* root systems maintain soil fertility. The hedgerows and dicotyledonous weeds possibly created a more favourable microclimate, possibly reducing mineralization of SOM, and their combined deeper root system may reduce nutrient leaching. Studies of the interaction of agroforestry and weeds has until recently concentrated on suppression (Yamoah *et al.*, 1986; Salazar *et al.*, 1993; Rippin *et al.*, 1994) but new research should investigate the role of weeds in the mediation of the C and nutrient cycles especially in dry seasons (Schroth, 1994).

3) Biomass production and Soil Organic Matter

The transformation of organic inputs leads to formation of SOM. The maintenance of adequate levels of SOM is one of the main components ofsoil fertility management in low-input land-use systems in the tropics, such as agroforestry (Young 1989a). The quantity and dynamics of SOM are affected by soil properties (Amato *et al.*, 1987; Ladd *et al.*, 1983)

Space

The maintenance or improvement of SOM provides such benefits as (Ingram, 1990):

- improved / maintained soil physical properties.
- improved ion exchange material.
- improved substrate for microbial action.
- improved source of inorganic nutrients.
- moderating effect on extreme soil reactions.

Young (1989a) estimated the biomass inputs required to maintain topsoil C assuming that the inputs contribute to the labile fraction (1/2 life of 3 years):

Humid tropics required	8400 kg dry matter residue ha^{-1} yr^{-1}
Sub-humid tropics required	4200 kg dry matter residue ha^{-1} yr^{-1}
Semi-arid tropics required	2100 kg dry matter residue ha^{-1} yr^{-1}

These estimates provide a method for comparing the potential of different systems and component species to conserve SOM and provides some measure of a systems' sustainability. Young (1989a) concluded from studying measured biomass production by multipurpose trees in agroforestry systems and plantations that soil organic matter could be maintained if the 'total' tree biomass is returned and if the crop residues are returned also. Harvesting the woody component makes SOM maintenance difficult and it becomes almost impossible if foliage and crop residues are removed. This reinforces the need to record the biomass production of the different tree components.

Ong (1994) compared 7 long-term alley cropping trials and noted that two of the trials sites failed (Claveria, Philippines and Kasama, Zambia) because the systems couldn't produce sufficient biomass due to high acidity or low rainfall. Of the others (Hyderabad, India and Machakos, Kenya; (both dry, semi-arid sites) the crops were out-competed by the trees. Yurimaguas, Peru and La Montana, Costa Rica produced cereal yields that did not exceed the controls. It appears that alley cropping is most suitable for food production on Alfisols and other moderately high, base-rich soils in the humid and sub-humid tropics. It is unsuitable for acidic soils or in semi-arid climates (Kang, 1993a).

5.4.4 Nutrient concentration

1) Above ground nutrient inputs

Leguminous trees in alley cropping systems producing 20 t dry matter ha^{-1} yr^{-1} dry matter, contain as much as 358 kg N, 28 kg P, 232 kg K, 144 kg Ca and 60 kg Mg (Szott *et al.*, 1991- see Table 5.6). This is more than enough to meet most crop requirements (Palm, 1995).

Nutrient content however depends on several factors such as tree species, the relative proportions of leaves and stems in the prunings, and their respective nutrient concentrations. Differences within a species can vary by a factor of two or more (Budelman, 1989). Such differences can be due to different provenances, soil fertility, climate, season, age of leaves or plant, frequency of pruning, or even differences in the methodology of laboratory analysis (Palm, 1995). Budelman (1989) suggested that soil nutrient status is the most important factor. He reviewed the information on nutrient content of *Leucaena leucocephala* and *Gliricidia sepium* leaves (Table 5.11).

Table 5.11 Average nutrient concentration (%) of *L. leucocephala* and *G. sepium* (Budelman, 1989).

	N	P	K	Ca	Mg
Leucaena leucocephala	3.84	0.20	2.06	1.31	0.33
Gliricidia sepium	3.82	0.23	2.80	1.42	0.46

Budelman's research highlights the need for combined nutrient content and biomass data. In field research *L. leucocephala* produced greater pruning biomass, 15,440 kg ha^{-1}, compared to *G. sepium's* 10,480 kg ha^{-1}. Although *G. sepium* has a higher nutrient concentration, *L. leucocephala* served as a better nutrient source for the crops (Budelman, 1989).

Can agroforestry tree species supply the nutrient requirements for a given crop species?
A common crop species researched within agroforestry systems is maize. The nutrient requirements for a 2 t grain yield, plus the associated 3 t stover growth are shown below in Table 5.12A. Assuming 4 t as a standard biomass input, examples of the nutrient levels provided by several different tree prunings and other organic sources (stover residue), are shown in Table 5.12B.

The N content of 4 t of leaf material is sufficient for 2 t maize grain (plus stover) in all but the two non-leguminous tree species and the maize residue. This mulch input rate is realistic as Table 5.7 shows (Szott *et al.* 1991). Tree prunings can generally meet the crop N requirements,even though as little as 14 %, and often less than 50% of the N, is from N-fixation (Giller and Wilson, 1991). If the crop residue is returned, all the agroforestry tree species can provide the nutrient requirements except for P.

Table 5.12 Nutrients required by a crop of maize compared to the nutrients contained in 4 t of organic inputs (Palm, 1995)

A. Nutrients required by a crop of maize (source: Sanchez, 1976)

	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}	Ca kg ha^{-1}	Mg kg ha^{-1}
Maize grain (2 t)	50	12	30	6	4
Maize stover (3 t)	30	6	36	9	6
TOTAL	80	18	66	15	10

B. Nutrients added in 4 t of leaves of various organic inputs (Palm, 1995).

Species	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}	Ca kg ha^{-1}	Mg kg ha^{-1}
Leucaena leucocephala	154	8	84	52	13
Erythrina poeppigina	132	7	46	61	-
Inga edulis (fertile soil)	142	11	40	45	6
Inga edulis (infertile soil)	127	9	50	30	7
Senna siamea	105	6	50	30	7
Dactyladenia barteri	60	4	31	40	8
Grevillea robusta	52	2	24	60	7
Maize stover	40	8	48	13	8

Salazar *et al.* (1993) discovered net negative P balances of 17 kg ha^{-1}, 19 kg ha^{-1}, and 21 kg ha^{-1} for *Inga edulis*, *Erythrina spp.* and *L. leucocephala* alley-cropped, rice systems (respectively) even with 20 Mg ha of dry prunings per annum on an alluvial Entisol. There were net positive balances for all other elements.

2) Phosphorus
P was not provided in sufficient quantities to meet crop demand by any source in Table 5.12.
In order to meet P requirements there must be either:

- greater pruned biomass

- greater P concentration in the biomass
- or an external supply.

Palm *et al.* (1991) examined P balance studies for various agroforestry systems Improved fallows studied by Szott (1987) at Yurimaguas showed only 2 of the 6 tree species tested (*Desmodium* and *Inga*) stored more P and produced greater biomass than the natural fallow. The increase indicated a transfer from unavailable to available P soil forms in order to satisfy the amount taken up and stored and possibly reflected different species' uptake kinetics and/or their ability to tap previously unavailable forms. Certain improved fallows have the potential to take up and store P more quickly than natural fallow. This benefit is further dependent on biomass accumulation capacity (Palm *et al.*, 1991). Sustainability, is still in question if P is exported in the crop.

Alley cropping systems have frequently resulted in a decrease in extractable soil P (Reynolds, 1994; Kang *et al.*, 1981; Szott, 1987; Haggar *et al.*, 1991). Atta-Krah (1990) found soil P levels declined faster in alley farming, with or without a grazed fallow period, than in conventional no-tree cropping. Haggar *et al.* (1991) studying alley cropping in La Montana, Costa Rica on a fertile soil, concluded that the P cycle was not stimulated by trees importing large amounts of nutrients from outside the system. Higher P availability to the crop was maintained through P release from the mulch, not from the soil, i.e. better cycling. This alley cropping system and the improved P cycle appears to be sustainable in the long-term but only with moderate fertilizer application (71 kg KCl ha yr^{-1}, 38 kg P ha yr^{-1} as triple superphosphate, and 10 kg Mg ha yr^{-1}).

Tree-crop production systems often impose high P demands. Heuvelop *et al.* (1988) recorded 4 kg P ha^{-1} yr^{-1} being extracted from cacao plantations in Costa Rica. Continued production was sustained through nutrient cycling via litterfall providing sufficient P to balance exports (see Table 5.13), and second P fertilizers were added at a rate of 29.3 kg ha^{-1} yr^{-1} (phosphate). Litterfall production and concentration may satisfy demand, but this was maintained through external inputs of P because the system was not self-sustaining (Palm *et al.*, 1991)

Table 5.13 P removed in fruit harvest and P in litterfall for 2 Cacao plantations (Heuvelop et al., 1988)

Nutrient extraction in cacao fruits:	kg P ha^{-1} yr^{-1}
T.cacao / C. alliodora	4.0
T.cacao / E. poeppigiana	4.3
Nutrients in litterfall:	
T.cacao / C. alliodora	13.9
T.cacao / E. poeppigiana	8.8

From their study Palm *et al.* (1991) concluded that large amounts of P extracted in product harvests, coupled with low P availability in most acid tropical soils makes P an important and potentially limiting nutrient in most agroforestry systems. Productivity in such situations is usually sustained through inorganic P inputs although some systems appear, on initial research, to remain productive through P cycling, transformation and

Rawat and Hazra (1991) conducted a 3 year, dryland, alley-cropping experiment with *L. leucocephala* and various crops. All of the cropping systems tested improved organic C status and available N and P over the 3 years. Alley systems with 2 inter-rows of crop increased considerably the available soil P, from 9.7 kg P ha^{-1} initially to 18.2 kg P ha^{-1} to 12.5 kg P ha^{-1} under monocropped pearl millet. However, all the cropping systems decreased available K.

3) Potassium

Generally 50% or more of K in the humid tropics is released from organic matter inputs in less than 1 month (Palm and Sanchez, 1990). K release is less affected by chemical characteristics and soil faunal activity, probably due to its high mobility.

There is obviously a great need for trees to capture and recycle this nutrient. *L. leucocephala* appears to be an efficient cycler, as indicated by changes in soil K levels under hedgerows (Dalland *et al.*, 1993; Van der Meersch, 1992). *Leucaena* reportedly supplied enough K to maize on low K status soils in S. Benin, when N and P was not limiting (Akonde et al., 1994). Osunubi *et al.* (1995) investigating mulched cassava yields alley cropped with *Senna siamea*, concluded that the lower root yield may be attributed to senna's low K yield compared to the higher cassava yield when alley cropped with *G. sepium* or *L. leucocephala*. However, Salazar *et al.* (1993) observed an exchangeable K decrease under *L. leucocephala*, *Inga edulis* and *Erythrina spp.* hedgerows despite net positive K system balances. Soil K decline was significantly reduced with mulching. Decrease in exchangeable K under several alley farming systems has been observed in comparison to conventional no-tree cropping (Kang *et al.*, 1981, Yamoah *et al.*, 1986; Atta-Krah, 1990).

4) High Nutrient concentrations

Some trees have shown potential for selectivity in accumulating certain nutrients. Sanchez *et al.* (1985) reported that litter and detritus from *Gmelina arborea* contained twice as much Ca as that of virgin forest or mature pine plantation. The Mg concentration was 3 times that of *Pinus* litter. Chijoke and Mayer (1980) reported 117 and 161 kg Ca ha^{-1} yr^{-1} returned in *G. arborea* litter for two plantation sites in Brazil. This ability to produce base rich litter provides the potential to ameliorate the productivity constraints to acid soils (Sanchez and Miller, 1986).

Other examples of significant nutrient accumulations include:

Palms and palm litter - rich in K	(Folster *et al.*, 1976)
Tree ferns accumulate N	(Mueller-Dombois *et al.*, 1984)
Cecropia spp. appear to accumulate Ca and P on acid sites	(Odum and Pigeon ,1970)
Dendrocalamus (bamboo) accumulates K	(Toky and Ramakrishnan, 1982)
Heliconia spp accumulate available P	(Tergas and Popenoe, 1971)
Lantana camara	(Buresh pers. comm)
Tithonia diversifolia	(Buresh pers. comm)

Such selective accumulations of plant-nutrient change with location and site / soil characteristics (Golley, 1986) and should be recognised when considering incorporating such nutrient conserving species.

5) Nutrient concentration of below ground litter.
Below ground litter represents another source of nutrients. There are very little data on the nutrient content of root residues, or the rates of residue addition to the soil (as already discussed).

Andriesse and Schelaas (1987) reported that the root system of Sri Lankan / Malaysian forest fallow contained 76 kg N ha^{-1}, 3.5 kg P ha^{-1}, and 53 kg K ha^{-1} equalling 14.5%, 18.5%, 15.5% respectively of the total forest content. In forest systems, fine root and mycorrhizal turnover can contribute 2-4 times more N and 6-10 times more P than above-ground litter (Bowen, 1984). This can be achieved through litter, organic acid, surface phosphate and siderophore production.

Studies by ICRAF (1995 Report) at Chipata, Zambia on *Sesbania sesban* fallows has produced root nutrient input values of 23.6 kg N, and 1.3 kg P for 1 year of growth. These nutrients are available for crop growth following decomposition and mineralisation. . However, the C / N ratio of root biomass varies much more than foliar biomass so that mineralisation may proceed at a slower rate thereby creating a prolonged residual effect.

5.5 Nutrient release

The rate of decomposition and nutrient release depends upon: first, temperature, moisture, soil texture and mineralogy. Decomposition is generally more rapid in warmer, more humid climates (Anderson & Swift 1983) and in sandy soils as opposed to soils of a high clay content (Amato *et al.* 1987) and the rate of application, placement, timing and quality of the organic inputs (Sanchez *et al.* 1989).

1) Above-ground litter quality
Resource quality is determined largely by chemical composition. For agricultural systems %N 1.73 or C / N ratio < 20 denotes good N mineralising crop quality (Sanchez *et al.*, 1989). For natural ecosystems, the lower the lignin to N ratio (LIG / N) the faster the decomposition and N release (Melillo *et al.*, 1982).

Studies focused on leaves of agroforestry trees have produced a wide range of initial %N release, immobilisation and mineralisation rates. The above indices do not always serve well to predict release patterns (Palm, 1995). Constandine and Fownes (1994) have shown that it is important to categorise material into leguminous and non-leguminous plants and also to distinguish between non-senesced leaves and litter, and senesced leaves. From tropical leaf material ranging widely in chemical composition, initial N concentration was best correlated with N accumulation/depletion. The other indices of carbon quality (polyphenols and lignin) exert a secondary effect within certain types of plant material.

2) Nitrogen Release
Laboratory incubation studies on agroforestry legume leaves (Fox *et al.*, 1990; Palm and Sanchez, 1991; Tian *et al.*, 1992a; Constandine and Fownes, 1994; Handayanto *et al.*, 1994) have provided preliminary indices for predicting relative amounts of initial N released or immobilised (e.g. Fig. 5.5.). Polyphenol and lignin content are inversely related to the N% released, i.e. both compounds lower the legume quality. A good

general guideline is taht if lignin concentration >15%, or polyphenolic concentration >3%, there is likely to be delayed N release (Palm, 1995).

Results from N mineralisation/immobilisation studies for 8 week incubation (except Tian *et al.*, 1992a, 7 week) gave the following results:

Gliricidia sepium	releases 30-70% N
Leucaena leucocephala (%N > 3.5)	releases generally < 25% N
Calliandra calothrysus	releases < 20% N
Inga edulis	releases < 20% N
Senna siamea (Non-N fixer)	immobilises up to 6 weeks, then releases 10-40 % N
Dactyladenia barteri	net immobilisation

(Source Palm, 1995)

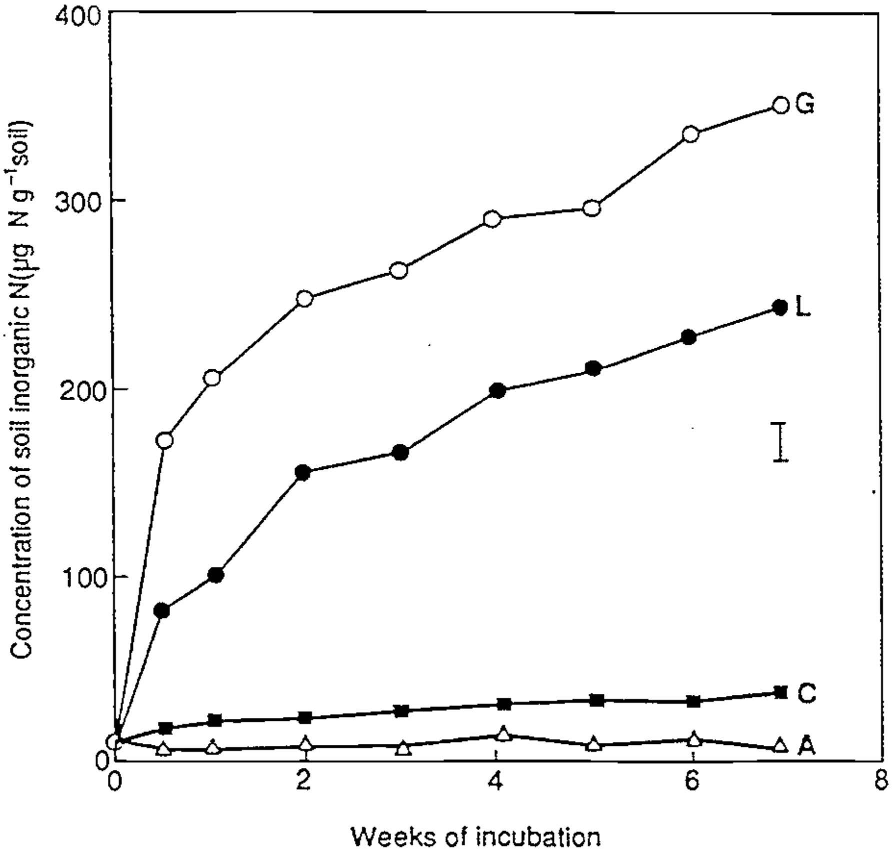


Fig. 5.5 Release of mineral N into the soil from the decomposing litters of three tree species, G (*Gliricidia sepium*), L (*Leucaena leucocephala*), and A (*Acioa barterii*), as compared with soil alone (C) (Tian *et al.*, 1992b).

3) Phosphorus and other nutrients

Most research work has focused on N with little attention paid to P or other nutrients. However, as the nutrient concentration data above has suggested, once nitrogen requirements are met, P becomes the limiting nutrient in many tropical soils (Palm *et al.*, 1991) However, P availability and mineralization are difficult to measure (Walbridge and Vitousek, 1987).

Palm (1988) has shown that patterns of loss for other nutrients besides N from legume residues can be affected by residue quality. Mineralization of P, K, Ca and Mg from pruned foliage of high quality *Erythrina spp.* isconsiderably more rapid than from pruned foliage of lesser quality *Inga edulis* and *Cajanus cajan.* 40% of P and Ca, and 75% of Mg was lost from *Erythrina* foliage in the first 20 weeks, whereas for the other two species, it took 32 weeks to reach the same degree of nutrient release. P release generally follows that of biomass, though there can be periods of immobilization (Palm and Sanchez, 1990; Tian *et al.*, 1992b), which can lead to soil solution P deficiencies relative to crop demand. Organic inputs can indirectly affect soil P availability by temporarily reducing the P fixation capacity of the soil (Singh and Jones, 1976), although the degree of this effect depends on litter quality. The potential to increase P availability either through decomposition or through reducing P fixation could be an important criterion for agroforestry species selection.

Laboratory research by Tian *et al.* (1992b) investigated 10 agroforestry and fallow tree species that all showed fast release of Ca and Mg (Sanchez and Palm, 1990). Four species showed noticeably higher release values: *L. leucocephala*, *G. sepiums*, *C. pubescens* and *M. prurings*. The Ca release rate related to that of N, rather than the initial Ca content (Fig. 5.6).

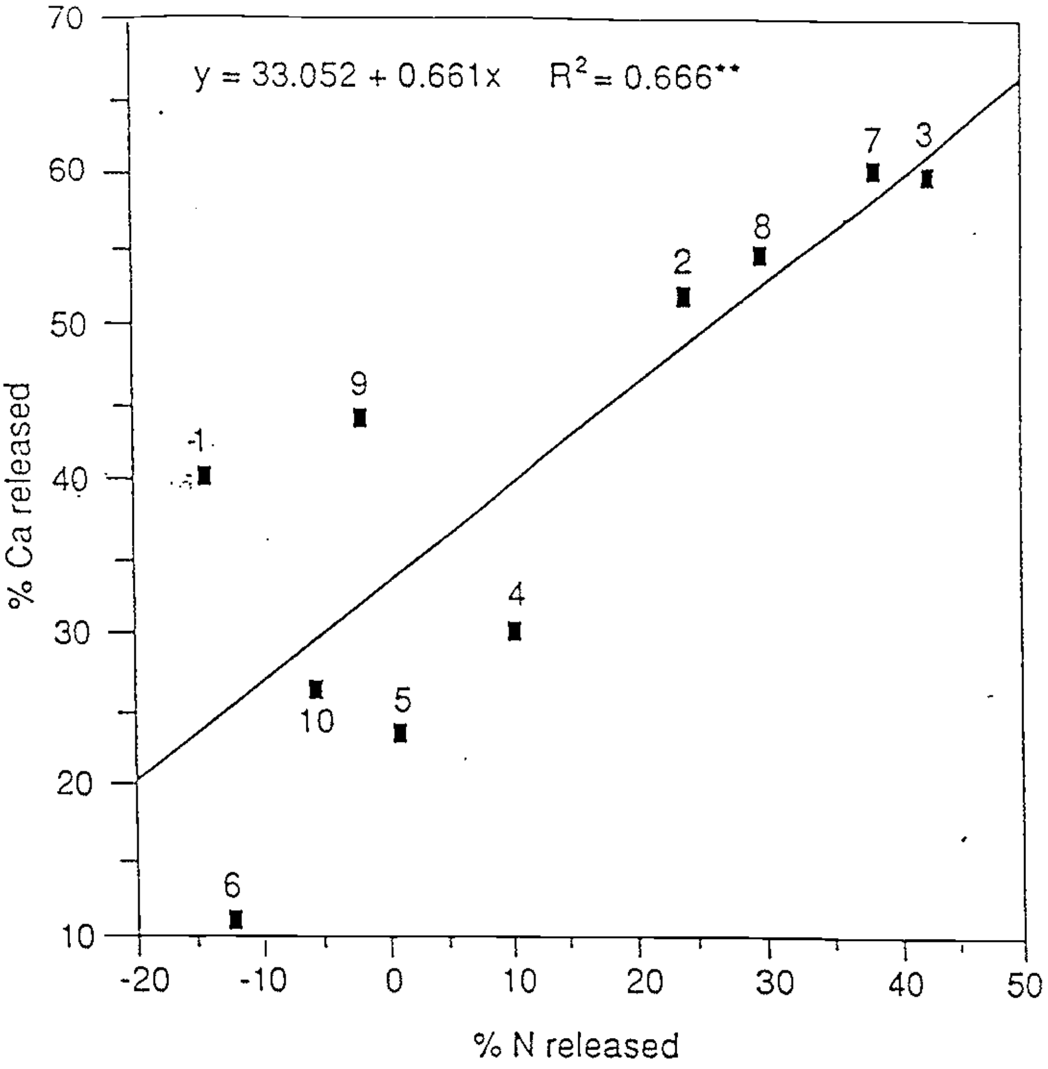


*Fig*5 . 5Relationship between N and Ca releases from leaves of fallow species following 7 weeks of incubation (1: *A. barteri*, 2: *L. leucocephala*. 3: *G. sepium*, 4: *C. siamea*, 5: *P. santalinoides*, 6: *D. guineense*, 7: *M. pruriens*, 8: *C. pubescens*, 9: *A. cordifolia*. 10: *A. macrophylla*).

Field experimentation by Tian *et al.* (1992b) investigating *L. leucocephala*, *G. sepium* and *Acioa barteri* release patterns after pruning concluded that except for K, release of N, P, Ca and Mg followed the same pattern as the loss of residue biomass. K release was extremely rapid, apparently irrespective of quality. Through the use of different mesh sized bags, the study was able to show that decomposition and nutrient release increased with increasing mesh size and therefore the presence of soil faunal activity. Earthworm activity has been shown to favour certain tree species (Saharan and Singh, 1988), organic C and available N being significantly enhanced. For 1 m around *Acacia tortilis* where casts were collected, 19 mg P_2O_5 and 192 mg K_2O were added as a result of earthworm activity. Much lower values were found for *L. leacocephala* agroforestry systems planted with a crop.

4) <u>Root litter quality</u>

Partly due to methodological difficulties it is uncertain whether root and leaf litter differ in quality, or whether root litter quality differs among vegetation types. In general, small diameter roots commonly produced by food crops would be expected to decompose and release nutrients rapidly, whereas decomposition and nutrient release from larger, more lignified root litter should be slower (Amato *et al.*, 1987).

Root litter quality from trees, may further differ from that of crops in the degree of homogeneity, proportion of fine roots, quantity of secondary or allelopathic compounds, nutrient concentrations, and the amounts of lignin and polyphenols present. Conventional indices of quality may not be suitable predictors of tree root decomposition (Szott *et al.*, 1991). Generally, leaf litter quality is higher and rates of decomposition are more rapid on more fertile soils. Litter from Spodosols and Psamments is often low in N, and that from Oxisols and Ultisols low in P (Vitousek and Sandford, 1987). Whether, similar patterns hold for root litter is unknown. There is an obvious need for research in this area.

Lehmann *et al.* (1995), compared the decomposition of leaves, twigs and roots of two diameter classes (1.5 mm, and 1.5-5 mm), from *G. sepium*, *Calliandra calothyrsus* and *Senna siamea* from an alley cropping experiment in Togo (plinthic Acrisol). The two diameter classes decomposed differently in all species. However, fine roots decomposed faster in *G. sepium*, whereas the coarse roots of *Senna siamea* decomposed faster than the fine roots. Mass loss of twigs and roots but not leaves can be attributed to termite activity, termites being very specific about which twigs and roots they prefer. The nutrient and C losses from termite activity neither improve SOM nor are available to the crop because the majority are immobilized in termite mounds (Lavelle *et al.*, 1992). The inconsistent impact of root diameter on decomposition may relate to different N concentrations (Camire *et al.*, 1991).

Roots may serve as a valuable source of nutrients, and their decomposition and nutrient release patterns can complement those of the leaves, although this is highly species dependent.

5.6 Synchronising Release and Demand (Timing)

As statedpreviously, nutrient release and availability depends on the rate of decomposition, application, placement, timing and quality of the organic inputs. To efficiently use and minimise the loss of nutrients supplied through above-ground litter prunings, 'synchrony' between nutrient supply and demand should be attempted by:

a) manipulating plant demand, through timing of planting and crop selection.
b) manipulating nutrient release, through timing of placement or the resource quality of the inputs (Myers *et al.*, 1994).

In shaded perennial crops or homegardens the problem of nutrient synchrony is important because perennial crop root systems are likely to be active most of the year (Szott and Kass, 1995). Plant materials could be selected to match the nutrient demand pattern for a specific crop. As high quality materials release nutrients rapidly large losses and low nutrient use efficiency can occur an effect similar to that of fertilizer application. Low quality organics release nutrients too slowly or insufficiently to meet crop demand. To achieve greater synchrony either intermediate quality organic material could be used, or a mixture of high and low quality materials (Swift, 1987 - Fig. 5.7).

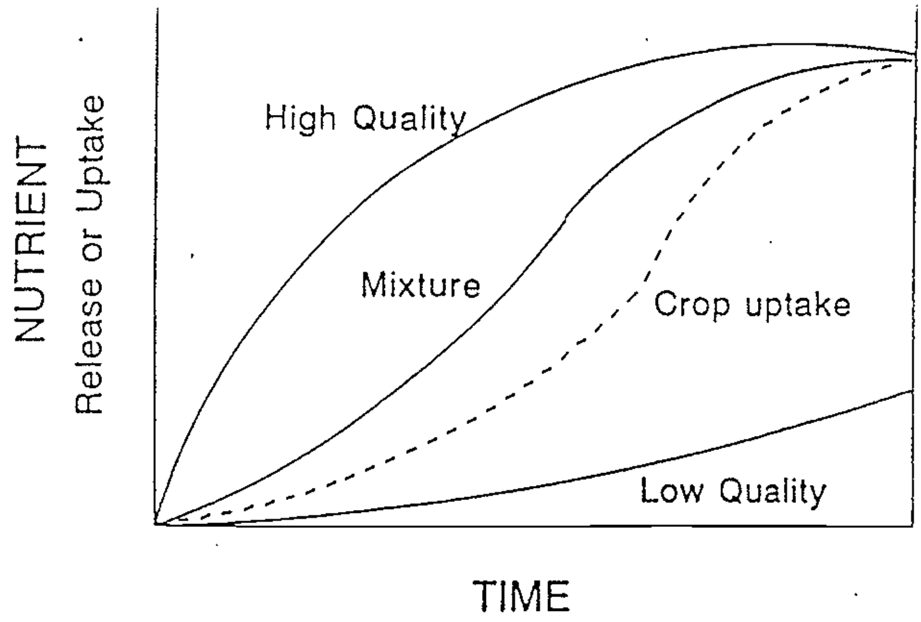
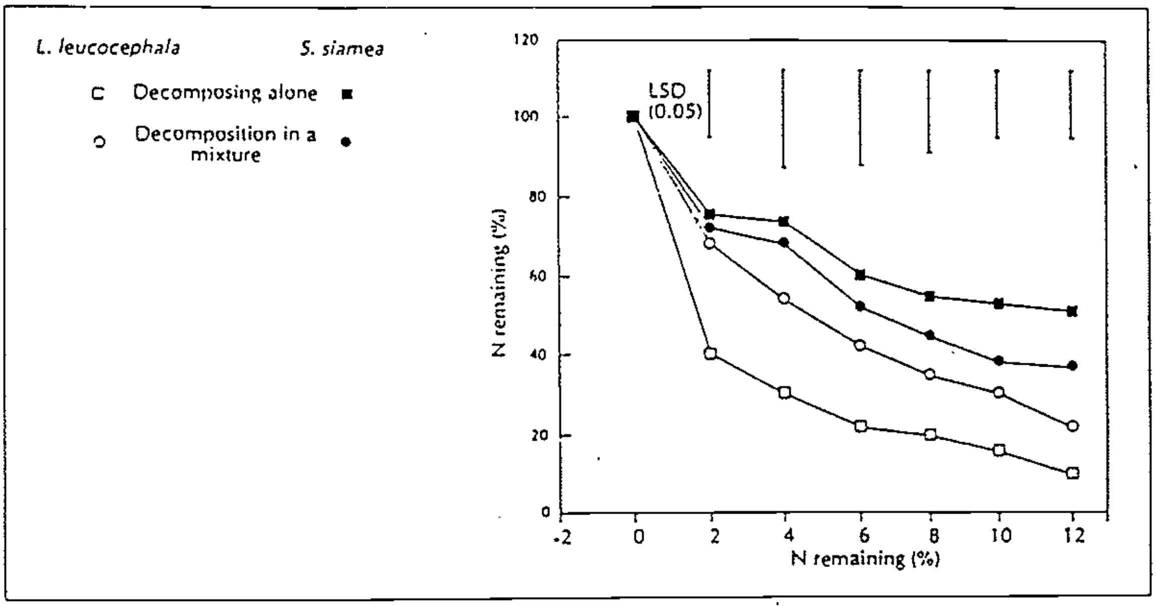


Fig.5.7 Hypothetical nutrient release patterns of different quality plant materials compared with nutrient uptake patterns (adapted from Swift 1987).

Most evidence suggests mixtures show release patterns similar to high quality materials rather than intermediary materials (Constandine and Fownes, 1994; Handayanto *et al.*, 1994). However, Myers *et al.* (1994) cite several studies that have produced intermediary release patterns upon mixing. One study, designed specifically to test the hypothesis in an agroforestry system, (Bandara and Anderson unpublished, cited by Myers *et al.*, 1994) compared N mineralisation from cereal straw and a *Gliricidia* legume, separately and mixed. The mixture released mineral N at an intermediate rate gradually increasing over the 12 weeks of the study.

Mulongoy *et al.* (1993) observed that the half life of *L. leucocephala* (C / N =11, lignin / N = 4) increased by 60 % when mixed with *S. siamea* (C / N = 15, lignin = 11) lower quality prunings, whose half life decreased by 43% (Fig. 5.8).

Fig 5.8 Nitrogen remaining in leaves of *Senna siamea* and *Leucaena leucocephala*, when decomposing alone or in a mixture with each other, at different times, as a percentage of initial N content



Mechanistic research is now necessary to understand the relative importance of nutrient release versus immobilization in determining the combined pattern of release of mixtures of organic materials (Myers *et al.*, 1994; Palm, 1995). For example, *S. siamea*, which has been shown to exhibit temporary immobilization, followed by rapid mineralization, may synchronise well with field crop demand.

For acid infertile soils, the incorporation of organic materials can also lead to improved control of soil Al toxicity, reducing exchangeable Al (Hargrove and Thomas, 1981), and converting Al in solution to non-toxic forms (Bell and Bessho, 1993). Such amendments can be further beneficial if the Ca and Mg concentrations are high, as in *Calliandra* (Bruce *et al.*, 1988; Bell and Bessho, 1993). Such high foliar concentrations may even be necessary as Sanchez and Miller (1986) noted that organic inputs could have a detrimental effect if the CEC is increased, without adequate addition of Ca and Mg.

5.7 Uptake of released nutrients

The primary purpose of biomass transfer is crop nutrient provision, but how much of the nutrients from this transfer are actually taken up by the crop? It is realised that efficiency in nutrient uptake is lower in more humid areas due to the greater leaching and denitrification loss, and higher in semi-arid environments (Myers, 1988).

Leguminous prunings have been shown to increase the yield of various crops, this is partly attributable to their N contribution (Yamoah *et al.*, 1986; Mulongoy and van der Meersch, 1988; Kang *et al.*, 1990; Sangakarra, 1989). The N contribution can be calculated as the difference between N content of alley cropped crops and that of the control crop and a wide range have been reported:

38 - 43 kg N ha^{-1}	from 3-4 t ha^{-1} of *Sesbania rostrata* (Mulongoy, 1986).
40 kg N ha^{-1}	from *L. leucocephala* and *G. sepium* prunings (Kang *et al.*, 1988)
4.4 - 23.8 kg N ha^{-1}	from *L. leucocephala* prunings (Mulongoy and van der Meersch, 1988)

Crop recovery values from the leaves of agroforestry tree prunings are generally around 20% or less, of the total N yield (Sanginga *et al.*, 1988; Mulongoy and van der Meersch, 1988 (< 10%); Haggar *et al.*, 1993 (10%)). These results are so low partly as a result of lack of synchronisation (Kang & Mulongoy 1992).

Fernandes *et al.* (1993) found no benefit to crop yield from applications of *Inga edulis* mulch, despite having accumulated much higher nutrient concentrations and reduce weed biomass in the alleys. This was again ascribed to lack of synchrony. Xu *et al.* (1992; 1993a and b), reported that *L. leucocephala* contributed just 3 -9% of N to maize in the 1st cropping season on a semi-arid tropical Alfisol (Australia). However, there was a noticeable (but decreasing) residual effect, leading to significantly higher yields over 3 successive years. Salazar (1991) observed a delayed crop response to low levels of P (25 kg/ha/yr) in an otherwise unfertilized *Inga edulis*, *Cassia reticulata* and *G. sepium* alley cropping systems on an Ultisol. Crop response was only shown after the 7th crop of an 11 crop sequence. Sisworo *et al.* (1990) working with a cowpea legume mulch observed that in addition to a direct crop response to N release there was a residual effect enabling between 44 % and 72% of the applied N to be eventually taken up by the crop. Such evidence supports the potential importance of immobilised N in the SOM.

Materials releasing large amounts of N initially have higher recoveries. However, as initial N release is large, the percentage loss may also be greater in comparison with lower quality material. To fully assess synchrony percent recovery and potential loss should be ascertained (Palm, 1995). Of the remaining 80 - 90% of applied organic N, a high proportion (up to 50%) may remain in the undecomposed material (Palm, 1995).

Mulongoy and Van der Meersch (1988) compared *L. leucocephala* alley cropped and monocropped maize, with and without prunings (Fig. 5.9). Of the N mineralised from *L. leucocephala* approximately 10% was taken up by the maize similar to the amount taken up from inorganic fertilizers (10 -30 The amount of N gained by the crop from the tree was in the range of 10 - 45 kg ha^{-1}, equivalent to between 0.65 and 3 tonnes of maize (Swift *et al.*, 1994). This is consistent with the yield responses observed in alley cropping studies at IITA (Kang *et al.*, 1990)

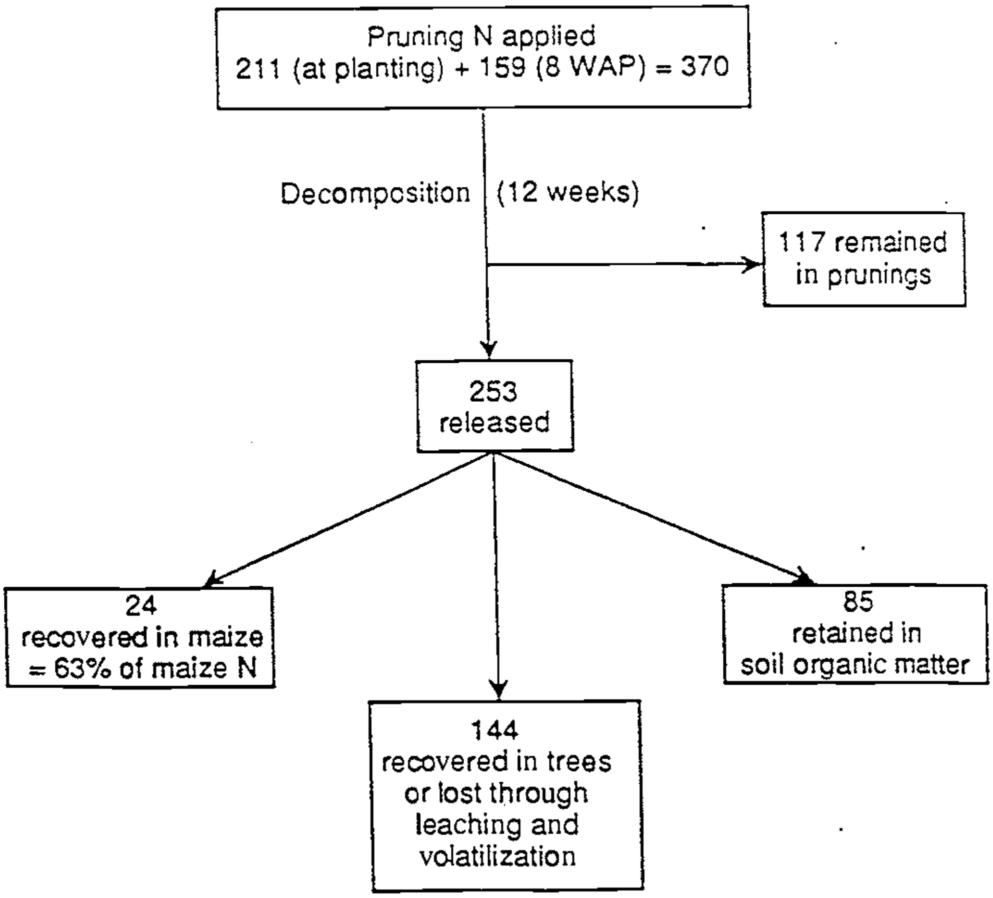


Fig. 5.9 A N budget for an alley cropping system - *Leucaena leucocephala* and maize (Mulongoy and Van der Mersch, 1988) WAP = Weeks after planting

Incorporation of the prunings has been shown to lead to more effective use of nutrients (Read *et al.*, 1985; Sangakarra, 1989) probably as a result of less N volatilization (Kang and Mulongoy, 1992). Tian *et al.* (1993) observed improved nutrient uptake when poor quality *Acioa barteri* prunings were applied to a Nigerian Alfisol. *Acioa* was noticeably more effective as a result of the indirect effects of decreased soil surface temperature and increased soil moisture.

Thus, high quality (low C / N ratio and lignin level) organic material inputs can directly affect crops through nutritional contributions, whereas low quality (high C / N ratio and lignin level) organic inputs can influence crops indirectly through improved microclimate (Tian *et al.*, 1993).

5.8 Organic and Inorganic Fertilizer combinations

Agroforestry systems that harvest large quantities of nutrients are unlikely to be sustainable without fertilization (Szott and Kass, 1995) especially on acidic, infertile tropical soils. On such soils the ability to increase nutrient status through efficient cycling appears to be limited as available nutrients for any system are low and toxic elements associated with acidity may be present (Sanchez, 1987; Palm *et al.*, 1991; Szott *et al.*, 1991).

On fertile soils, nutrient depletion will still occur but the capacity to balance the removals through reduced nutrient extraction and increased nutrient inputs (organic or replacement inorganic fertilizer) can be achieved (Szott and Kass, 1995). Tian *et al.* (1993) found nutrient uptake and grain yield of maize was higher when N was supplied partly as prunings, and partly as inorganic fertilizer, indicating the possibility of improving crop production yet further through combined additions.

Organic inputs cannot act as a total substitute for inorganic N, though Sangakarra (1989) found mulch application enhanced yields under all levels of N fertilizer application. Similarly, Xu *et al.* (1993a,b) found a positive interaction between N fertilizer application and *Leucaena* prunings, expressed as increased maize yield.

Cooper (1993) constructed factorial trials to investigate different *Leucaena* mulch and N fertilizer input amounts upon maize crops. The comparative results were 10 kg maize gran / kg leacaena mulch compared to 27.5 kg / kg inorganic N. There was no significant synergistic interaction when combined. Positive interactions may be crop specific Danso and Morgan (1993) studying maize and rice production in *Cassia siamea* alley cropping systems noted that maize yield responded positively to fertilizer and pruning application whereas rice showed no yield benefit from combined application.

<u>Organic Fertilizers</u>

Haggar *et al.* (1993) studying *G. sepium* and *E. poeppigiana*, concluded that the majority of applied organic N is incorporated into the SOM reserve of mineralizable organic N. 15N analysis showed that this was not incorporated into the microbial organic fraction, therefore little is taken up by the maize crop in that cropping season (15% of mineralized N). The long term build up of this SOM mineralizable N reserve appears to be more important than synchrony (Haggar *et al.*, 1993; Ladd *et al.*, 1981), so experiments are required that compare the effects of material quality on the different SOM fractions, and the subsequent residual effects (Palm, 1995).

The recovery values for N are generally less than those for fertilizers, but organic inputs contain C substrates for micro-organism activity so that much of the N released and not utilised by the crop is 'saved' as soil organic N, as opposed to being lost through leaching and denitrification (Sanchez 1995).

The nutrient benefit to crops from tree prunings comes more from the long term increase in SOM reserves than short-term release from the organic inputs. This favours agroforestry in terms of long-term sustainability The potential for improving N management requires quantification, through measuring such processes as mineralization, immobilization, denitrification, volatilization, leaching loss, and changes in soil organic N pools, for systems combining sole/mixed organic inputs, as well as combined organic and inorganic applications (Sanchez ,1995). NFTs may not be the best choice of agroforestry tree species. There is evidence that non-fixing trees, including species of *Cassia* (*senna*), accumulate as much or more N than N-fixers, (Szott *et al.*, 1991; Garrity and Mercado, 1994; Ladha *et al.*, 1993).

Garrity and Mercado (1994) investigating NFTs and non-leguminous tree biomass and nutrient contents over 4 years in hedgerow systems and concluded that NFTs did not have a significant advantage. The prunings of non-fixing species contributed more N and P to the annual crops. Factors other than N-fixation may be more important determinants in the selection of tree species. Ladha *et al.* (1993) estimated that the proportion of N in the *Gliricidia* plant from N-fixation was between 30 - 60 % of total plant N. Non-fixing tree species cannot increase this available N pool but compensate through recycling N already in the system more rapidly and efficiently. How long such a mechanism can meet system N requirements is not known and long-term studies are required (Garrity and Mercado, 1994).

The competitive pressure from NFTs has been observed (ICRAF, 1994) and is generally greater than that of non-fixing trees. NFTs have an inherently higher demand for P, thus, theoretically, creating high competition with the crops for P. This a factor of great significance in P deficient soils (Garrity and Mercado, 1994).

Inorganic fertilizer application

Fertilizer application is theoretically possible in agroforestry systems but the labour and capital costs limit the use to systems including a cash revenue component (Raintree, 1987). Applications are possibly close to a source of inorganic fertilizer but infrastructure is often a limitation away from cities.Before applying inorganic fertilizers, the available organic sources should be used to their full potential (Sanchez, 1994).

Szott and Kass (1995), based on studies of forest fertilization in temperate climates, predicted that the response of agroforestry systems to fertilization with inorganic N would be shorter (of the order of 3 years or less) than that observed for P. This is due to the immobilization of N and /or the large N losses that may occur under humid climatic conditions, especially if tree/crop uptake capacity is exceeded. In humid climates this risk can be reduced through frequent low-level application which is considerably more costly. Slow ammonium-release fertilizers are recommended for such situations. Response to P fertilizer application should be longer lasting, as P additions are usually large relative to available P in the soil (Szott and Kass, 1995), although this varies with the P-fixing ability of the soil. Acidic soils, with high immobilization capacities should receive slow release organic residue or rock phosphate forms.

It has been shown that agroforestry cannot supply all of the crop P requirements (Palm, 1995). Deep nutrient uptake of P is likely to be negligible, as subsoil concentrations are low (Kessler, 1979) especially on acid, infertile, deeply weathered soils. The situation is further aggravated by the fact that many agroforestry crops accumulate P in the harvested component. To illustrate this in a basic grain crop, the proportion of P recycled back to the soil assuming complete residue return is 38%, compared to 54%N, 89%K, 95% Ca and 70% Mg (Sanchez and Benites, 1987). After several harvests, P will become the critical nutrient in most agroforestry systems limiting productivity. The conclusion is that inorganic sources of P must be applied.

5.9 Modelling Agroforestry Nutrient Budgets

Currently, quantitative modelling research is attempting to explore which agroforestry systems and improved organic residue systems could improve soil fertility, whilst being ecologically and economically viable. Much experimental work testing the proposed hypotheses is done at the plot level which may ignore the limits of nutrient availability at a farm or regional scale. Therefore, thorough analysis of improved agroforestry systems and management practice through quantitative modelling of nutrient cycles / budgets at regional and farm scales is required and informative (Smaling *et al.,* 1993; Frissel, 1977; Swift *et al.*, 1989).

Table 5.14 Estimated soil N and P budgets for the field soil in 7 different farm systems (kg ha^{-1} yr^{-1}) (Shepherd *et al.*, in press)

	Farm System						
N Flow	1	2	3	4	5	6	7
Sum field inputs	23	499	21	93	114	146	243
Sum livestock inputs	15	15	15	15	15	15	0
Sum field harvests	28	47	32	92	38	77	58
Sum livestock harvests	10	10	10	11	10	12	111
Sum field losses	62	62	84	62	51	93	82
Sum livestock losses	28	28	28	29	28	33	33
Fodder to livestock	34	34	35	38	34	44	278
Manure to field	12	12	12	13	12	14	144
FIELD BALANCE	-89	-83	-118	-86	+3	-54	-41
P Flow	1	2	3	4	5	6	7
Sum field inputs	1.0	1.0	1.0	1.0	1.0	21	21
Sum livestock inputs	1.5	1.5	1.5	1.5	1.5	1.5	9.6
Sum field harvests	3.9	7.5	4.5	10.5	4.7	10.4	7.0
Sum livestock harvests	1.6	1.6	1.6	1.7	1.6	1.9	21.9
Sum field losses	3.7	3.7	3.7	3.7	0	3.7	0
Sum livestock losses	1.2	1.2	1.2	1.2	1.2	1.4	2.7
Fodder to livestock	3.7	3.7	3.8	4.1	3.7	4.7	39.2
Manure to field	2.4	2.4	2.5	2.6	2.4	2.9	24.1
FIELD BALANCE	-7.9	-11.5	-8.6	-14.7	-5.0	+5.0	-1.0

Farm system 1=standard, 2=boundary planting, 3=natural fallow, 4= improved fallow, 5=hedgerow intercropping, 6=high fertilizer inputs, 7=dairy-agroforestry system.

Shepherd *et al.* (1996a) has used a static model of nutrient flows to represent mixed farms in the humid highlands of western Kenya. A series of improved farm systems were examined for their potential impact on the nutrient budget (Table5.14). The soil nutrient balances of standard farm systems were -107 kg N and -8 kg P ha^{-1} yr^{-1}. Agroforestry did not significantly reduce the N deficit unless a large proportion of total biomass was returned to the soil. Agroforestry systems notably increased the N input through biological N fixation and deep N uptake but this was benefit was cancelled out by a larger nutrient removal in harvested products which increased from 38 kg N removed to 169 kg N in the dairy-agroforestry system. Agroforestry did not increase P inputs and P demand actually increased from 6 kg in the standard farm to 29 kg P ha^{-1} yr^{-1}, in the dairy-agroforestry system. Stocks were only maintained or slightly improved through moderate system inputs of 20 kg P ha^{-1} yr^{-1} .

The N budgets were very sensitive to N mineralization rates in the subsoil, N losses from soil and manure and the effectiveness of deep N root uptake, thus highlighting these areas as prime research topics.

6. CONCLUSIONS AND RECOMMENDATIONS

The foregoing review of literature serves to illustrate the complexity and diversity of the Forest/Agriculture interface, and perhaps provides an indication of why there have been only limited attempts to summarise the behaviour of the soil at this interface. The interface includes a wide range of activities, which vary to a considerable degree in the relative importance of trees and agricultural crops, the spatial and temporal extent of the interface, and the extent to which the systems are to be maintained with or without external inputs. The types of activity vary from the basic short-term clearance of forest for a limited duration cropping phase, followed by abandonment, with possible return at some time long in the future; through agricultural encroachment at the forest edge for continuous production; management of woodland spatially discrete from agricultural crops, such as the Miombo woodland of southern Africa; the tree gardens widely found in south east Asia; agroforestry practices such as alley cropping; and tree management systems such as plantations where agricultural crops are mixed either spatially or temporally. Most of these activities would conveniently fall under the broad heading 'Agroforestry', and it is important to note this, as frequently the term appears to be used in the very narrow sense to describe alley cropping. The practice of alley cropping is just one of the many activities called agroforestry, and experimental plots apart, is probably not of major importance when considering farmers in the tropics and sub-tropics.

In attempting to develop land use and management strategies for the Forest/Agriculture interface, it is imperative that the broad characteristics of the trees and agricultural crops are clearly identified. Further, the very nature of the interface requires that these strategies must take account of the interactions between the two components. These characteristics of the individual components and the nature of the interactions must be identified above and below ground.

The decline in soil fertility is a significant feature of many smallholder farming systems at the Forest/agriculture interface in the tropics and sub-tropics. This process of decline must be addressed and solutions identified if attempts to increase agricultural production from these systems are to be successful. In many cases the smallholder systems include no external inputs of nutrients and, as a consequence, their ability to maintain agricultural production is dependent upon the inherent fertility of the soil, the ability of the perennial (tree) root system to 'mine' nutrients from deep in the profile, and possibly some biological nitrogen fixation. As much of the land currently occupied by smallholder farmers and areas likely to be incorporated into agriculture in the future are underlain by soils such as Oxisols and Ultisols with inherently low fertility, the time period during which crop production might be maintained from internal nutrient sources alone is likely to be relatively short (indeed this is the driving force behind shifting cultivation). In many systems there is little knowledge of the nutrient pool available or the nutrient export in crops, it is therefore virtually impossible to predict the time taken for unsustainability to occur.

Nutrient depletion and consequent poor yields is often the precursor for other negative effects to occur. The reduction in yields will be accompanied by a reduction in associated residues which may result in lack of fodder for animals, and an unprotected soil surface resulting in an increased vulnerability to erosion. If the land is abandoned because of this degradation further land will need to be brought into production, with the likely consequence that this will be subject to the same degradation processes.

Identification of gaps in our knowledge and research foci

The gaps in our understanding of the systems and the research priorities are presented under broad headings:-

General Comments

1. Sanchez (1995) presents 16 'Soil Agroforestry Hypotheses' (see Section E, page 2). Evidence to support these hypotheses is exceptionally limited both in amount and in regional scope.

2. The soil is the basic resource of the Forest/Agriculture interface system, attention must focus upon the direct measurement of soil processes within the soil if the system~~s~~ is to be managed efficiently and successfully.

3. Sustainability is a long-term consideration, it is therefore essential that long term monitoring of soils under systems at the Forest/Agriculture interface be established. These studies should focus on both the potentially vulnerable soils and soils which are expected to support long term sustainable production, with a range of tree-agriculture combinations.

4. An alternative to long-term monitoring is the use of computer based models. At present it would appear there is insufficient understanding of the processes involved and as a consequence a scarcity of information which might be used to validate such models.

Research foci

A. Soil Nutrients

1. In recent years much of the attention of plant nutrient dynamics has focused upon the major nutrient, Nitrogen. In recent years it has become apparent however that Phosphorus may be a major limiting nutrient in the tropics and sub-tropics and hence is potentially of major importance in agricultural systems at the forest/agriculture interface. There is no process for P equivalent to 'biological nitrogen fixation'! P supplies in soil are from weathering and from organic matter. In many well-weathered soils of the region there are insufficient soil based supplies of P to meet plant needs. In addition the often high content of iron and aluminium oxides leads to substantial fixation of P.

Research Needs*: There is a need to more fully understand*
a. the dynamics of P in the inorganic-organic soil system
b. To consider the application of a wide range of rock based P sources

2. Whilst the cycling of nitrogen has been extensively investigated in tropical and sub-tropical soil systems, an important process in soils where perennial roots occur is deep nitrate capture.

Research Needs*: There is a need to investigate the process of 'deep nitrate capture' and to identify the nature of rooting systems required to optimise the efficiency of these systems.*

this is also exhaustible

3. There is very little quantitative evidence of nutrient pools, inputs and outputs from systems at the forest/agriculture interface. These data are essential if ~~an~~ efficient nutrient management is to be achieved.

Research Needs*: There is a need for a more complete understanding of nutrient budgets.*

4. There is a need for concerted action to document nutrient inputs/outputs as forest is cleared for agriculture. In particular this needs to be undertaken for Oxisols as these soils appear least likely to sustain continued agricultural production following clearance.

Research Needs*: To monitor the changes in soil nutrient pools in the post forest clearance phase.*

5. On many soils of the tropics low levels of output of agricultural products will be the norm if the systems are managed on a basis of zero external inputs. Whilst high levels of fertiliser inputs are probably inappropriate, strategies must be developed to effectively and efficiently use fertiliser inputs to promote sustained agricultural production in the production.

Research Needs*: To establish extensive field trials to consider the optimum management of organically based and fertiliser based nutrient inputs.*

B. Roots

1. Trees appear to have a significant role in 'closing the nutrient cycle' in tree/crop systems. This includes their role in preventing leaching losses through the base of the system and their role in recycling nutrients through transfer from deep in the soil into the leaves and other above ground components.

Research Needs: *To investigate the morphology and nature of tree root systems necessary to optimise the roots' role in 'closing the nutrient cycle'.*

2. Roots provide an important source of organic matter and nutrients in the soil. The below ground turnover of biomass is a potentially important process in many tropical and sub-tropical systems.

Research Needs: *There is a need to understand the distribution, decomposition and nutrient release patterns of both perennial tree and annual crop root systems.*

3. The below ground competition between tree and crop roots must be more fully understood in relation to root distribution and function. In particular it is essential that the below ground consequences of the above ground components of woody species be understood where there are agricultural crop roots present.

Research Needs: *To investigate under field conditions the nature and dynamics of the interaction between tree and arable crop root systems, both under normal and stressed conditions. The different root architectures and nutrient and water capture strategies must be identified.*

C. Soil Organic Matter

1. Information on the rates of nutrient release from soil organic matter and fresh litter is an essential requirement for successful management of the soil organic matter and litter resources.

Research Needs: *There is a need for mechanistic research of the release and immobilisation of nutrients in organic residues added to the soil both as soil surface and below ground additions.*

2. A major constraint for crop production in many soils is soil acidity and the associated soil conditions. Recently completed research for ODA's Forest Research Programme (Project No:R6071/R4754; S. Nortcliff and M.T.F. Wong 'The control of soil acidity in agroforestry systems') has shown the varied potential of a range of agroforestry residues in ameliorating high exchangeable aluminium levels in acid tropical soils (Wong *et al.*, 1995). The variability in the ability of plant residues to ameliorate the effects of exchangeable aluminium on plant yields, suggests that further investigation is necessary to characterise the nature of plant residues with respect to their influences on soil properties and processes.

Research Needs: To characterise the nature and composition of plant residues with respect to their 'liming effect', and to investigate response in both field and laboratory environments.

3. The ability of tree plants to produce different amounts of biomass for application to cropped land has been long known. Quantity alone provides insufficient information, more data are needed on the nature of these biomass additions and their rates of breakdown. There is a need to match the release of nutrients from plant materials with the needs of the crop plant and soil. n/

does the soil have needs.

Research Needs: To characterise the nature of the plant residues, the rate of breakdown of the residues and the release of nutrients during this breakdown. and to synchronise these releases with the needs of the crop plants and soil system.

4. It has long been established that fallows are an important component in the regeneration of degraded soil systems. The periods of fallow are becoming increasingly shorter because of the pressure on land. It is necessary therefore to more actively manage the fallow species to optimise the ameliorative effects of the fallow.

Research Needs: To investigate the beneficial effects of fallow tree species and identify the extent to which particular trees may be used for ameliorating soil with respect to particular nutrients. To develop a management strategy on this basis.

5. Soil organic matter and litter are subject to decomposition processes throughout all or parts of the year. The dynamics of litter breakdown need~~s~~ a fuller investigation. ℓ/

Research Needs: To monitor the nature and dynamics of soil organic matter and plant litter over seasons and longer time periods.

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ADDITIONAL REFERENCES

R6384 Follow-up papers:
Stephen J Livesley, Department of Soil Science, University of Reading (three related papers to be submitted by April 1998; full references not yet available).

1. "Below-ground interactions in a maize-based tree boundary agroforestry system:
I - Tree and crop root distribution and dynamics."
2. "Below-ground interactions in a maize-based tree boundary agroforestry system:
II - Tree and crop nitrogen demand and soil nitrogen supply."
3. "Below-ground interactions in a maize-based tree boundary agroforestry system:
III - Soil water distribution and dynamics."