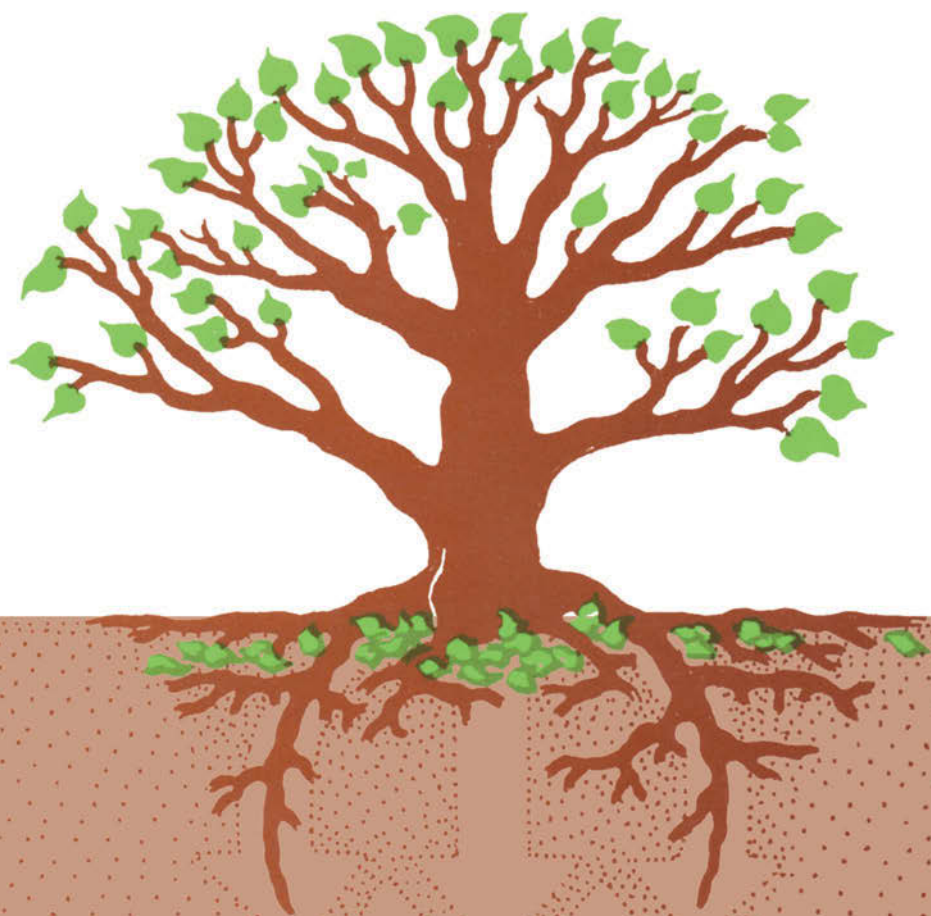


# Amelioration of Soil by Trees



Commonwealth Science Council

**AMELIORATION OF SOIL BY TREES**  
**A REVIEW OF CURRENT CONCEPTS AND PRACTICES**

**Edited by R T Prinsley and M J Swift**

**Commonwealth Science Council**  
**Commonwealth Secretariat**  
**Marlborough House**  
**London SW1Y 5HX**

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## CHAPTER I

### INTRODUCTION

J I Furtado, M J Swift and R T Prinsley

In formulating the strategy for the expanded Commonwealth programme on science and technology in 1984, the Kendrew Report on "Science for Technology for Development" (1984) and the 13th biennial meeting of the Commonwealth Science Council in Ottawa, Canada, recommended inter alia the promotion of:

- methods for extending and expanding agriculture on unsuitable lands;
- agricultural research in a few areas where a major impact is possible;
- fresh incentives to good agricultural scientists for enhancing their own agricultural research;
- the study of the relationship of water resources, soil water and agrometeorology to plant growth and reproduction;
- programmes to arrest the present degradation of tropical forests.

In 1981, the African Natural Products Programme of the Commonwealth Science Council (CSC) was established with the objective of exploiting the rich, untapped resources of Africa. This coincided with the recognition by CSC of the increasing problems of severe food shortage, high imported energy prices, depletion of indigenous fuelwood resources, the loss of productive land through desertification and the threats of extinction of diverse plant genetic resources. Agroforestry, an integrated land use system comprising of trees, crops and/or animals, and providing for resource conservation, was seen by CSC to offer an appropriate scientific approach to the issues of natural resource 'exploitation' and conservation in Africa. The agroforestry programme was developed further by CSC in 1983 at a meeting in Malawi, and because of the strong interest and history in agroforestry research in Asia, has now also extended to this region.

This initiative coincided with the launch of the "Decade of the Tropics" programme by the International Union of Biological Sciences (IUBS) in 1983, to improve the efficiency of food production in the tropical zone in view of a burgeoning human population with increasing land shortage, living in an area of low productivity and income, and threatened by famine because of low agricultural productivity and increasing global food demand (Solbrig and Crolley 1983).

One of the segments of the "Decade of the Tropics" programme concerns soil biological processes and tropical soil fertility (Swift 1984). The objective of this programme segment is to determine the management options for improving tropical soil fertility through biological processes in three broad 'zones':

- the humid tropics dominated by rain forests;
- the sub-humid tropics dominated by broad-leaf tree savannas;
- the semi-arid tropics characterised by thorn or other xeromorphic bush savanna.

It aims to gain an understanding of the soil system, nutrient cycling, modification of soil physico-chemical properties, biological processes in relation to management, and soil biological processes in relation to cultivation.

The Tropical Soil Biology and Fertility (TSBF) programme outlines principles and management options that are already known (Table 1), testable hypotheses in relation to these principles (Table 2) and three levels of increasing intensity of research (Table 3). Some illustrative examples by which management practices can manipulate soil biological processes have been taken into consideration in formulating the TSBF programme (Table 4). In view of this and of the Commonwealth Science Council's long-standing interest in agroforestry systems for food, fodder, fibre, biomass, energy and optimisation of land use, the Council organised a workshop and planning meeting in Lucknow, India, in March 1986, on "Amelioration of Soils by Trees". The proceedings and recommendations of this workshop and meeting have been published (CSC 1986). This volume represents the collection of papers refereed and edited, that were presented at the workshop and meeting on the "Amelioration of Soils by Trees".

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**TABLE 1**

**Principles (P) and Management Options (MO) in relation to  
Tropical Soil Biology and Fertility (Swift 1985)**

- P1:** The release of nutrients (N, P) from above- and below- ground litter can be synchronised with plant growth demands.
- MO1:** The efficiency of nutrient availability to the plant can be manipulated by varying the quantity and quality of litter (e.g. crop residues, manures, etc) and the time of its input in relation to the onset of rain.
- P2:** Soil organic matter constitutes both a sink and a source of plant nutrients (N, P), and hence acts as a regulator of temporal and spatial patterns of nutrient availability. The quantity and quality of soil organic matter is influenced by the nature of the above- and below- ground litter input.
- MO2:** The quality and quantity of soil organic matter, and thence the timing, location and magnitude of nutrient availability can be regulated by management of litter inputs.
- P3:** The pattern of root growth in time and space acts as a regulator of the availability of nutrients to plants in present and future seasons.
- MO3:** Management practices which retain root litter in the rooting zone, and relate new plantings to the location of previous ones, will improve soil fertility.
- P4:** Surface litter and soil organic matter influence soil water fluxes and moisture regimes.
- MO4:** The soil water regime may be improved by management of litter inputs both through direct effects and by indirect influence on the soil fauna.

**TABLE 2**

Testable Hypotheses in relation to Tropical Soil Biology  
and Fertility Principles (Swift 1985)

- H1: The rate of decomposition and nutrient release of a particular litter within any site is primarily controlled by moisture, and is most closely related to the onset of rainfall (P1).
- H2: Increasing the proportion of low-quality (eg low N and P, high lignin content) litter inputs at the onset of rains extends the time period of availability of nutrient to the plant (P1).
- H3: The availability of nutrients to plants (eg from inorganic fertilizers) can be delayed through microbial immobilisation on low-quality litters, thence decreasing the risk of losses through leaching (P1).
- H4: Increasing the proportion of low-quality litter results in increased soil organic matter pools particularly of the more recalcitrant fractions (P2).
- H5: Increased availability of nutrients to the plant (eg from inorganic fertilizers) results in increased quality of litter inputs and reduces the recalcitrant pool of soil organic matter (P2).
- H6: Increased soil organic matter results in an increase in the time period of nutrient availability to plants even in the presence of high-quality litters (P2).
- H7: Below-ground litter is a more important source of immediately available nutrient than above-ground litter (P3).
- H8: Below-ground litter contributes a relatively greater component to soil organic matter formation than above-ground litter (P3).
- H9: Detritivores affect the vertical distribution of litter in the soil, and thence the availability of the nutrient to plants on release (P3).
- H10: Above-ground herbivores change the timing of litter inputs and positively raise its quality, thence increasing the rate of decomposition and nutrient release and decreasing the contribution to soil organic matter formation (P1, P2 and P3).
- H11: Surface mulching encourage soil fauna which positively influence the structure and hydrological characteristics of the soil (P4).
- H12: Maintenance of litter in the rooting zone improves the physical structure of soil (P3 and P4).

**TABLE 3**

Levels of Increasing Intensity of Research in the  
Tropical Soil Biology and Fertility Programme (Swift 1985)

Level I is the minimum level of participation in the programme, and involves an investigation of the various features of nutrient cycling in the plant-litter-soil system:

- site characteristics (site selection and description, soil characteristics, climate and soil environment, vegetation, soil fauna);
- organic matter and nutrient element inputs (above-ground inputs, below-ground inputs);
- decomposition (above-ground resources, below-ground resources);
- plant growth and nutrient uptake (above-ground, below-ground);
- soil processes (soil organic matter fractions, nutrient availability, soil water regime and nutrient leaching).

This is to be achieved by means of a broad comparative study of natural and managed ecosystems.

Level II involves the specific experimental testing of one or more of the testable hypotheses, in addition to the minimum Level I description.

Level III involves the intensive investigation of one or more of the testable hypotheses in addition to the minimum Level I description, as well as detailed study of some particular aspects of soil biology, such as:

- input of N by dinitrogen fixation
- uptake of nutrients by mycorrhiza
- gaseous loss of N
- soil organic matter quality, stability and lability
- soil fauna studies
- soil microflora studies.

**TABLE 4**

Major Soil Biological Processes with Examples of Management Practices  
by which the Process can be Manipulated (Swift 1984)

	<u>Soil Biological Process</u>	<u>Management Practice</u>
1.	Root turnover	Fertilisers increase root production
2.	Root exudation	Crop species differ in the nature and amount of exudates
3.	N <sub>2</sub> -fixation	Legume fallows
4.	Nutrient translocation	Tree fallows induce upward movement of nutrients
5.	Litter decomposition (comminution)	Insecticides reduce detritivore populations
6.	Litter decomposition (enzymatic catabolism)	Tillage increases biological oxidation
7.	Humification	Incorporation of low quality residues promotes synthesis of organic colloids
8.	Nutrient immobilization	Incorporation of low quality crop residues
9.	Grazing by soil fauna	Insecticide treatments decrease faunal mobilization and increase microbial immobilization
10.	Soil organic matter decomposition	Lime application increases rate of soil organic matter decomposition
11.	Mineralization and mobilization	Burning increases mobilization
12.	Solubilization	Addition of S increases solubilization of rock phosphate by <u>Thiobacillus</u>
13.	Nitrification	Drainage increases nitrification
14.	Denitrification	Increased by nitrate fertilization in humid soils
15.	Oxidation or reduction of S, Fe, Mn, etc	Incorporation of nutrient rich residues increases reduction processes

- |     |                           |   |
|-----|---------------------------|---|
| 16. | Nutrient uptake           | Mycorrhizal inoculation increases nutrient uptake                           |
| 17. | Soil particle aggregation | Addition of crop residues (animal and microbial effects)                    |
| 18. | Soil surface capping      | Heavy grazing bares the soil surface and increases microfloral capping      |
| 19. | Soil pore development     | Addition of organic residues maintains populations of macrofauna            |
| 20. | Soil particle movement    | Termites reverse clay illuviation; tillage pesticides destroy termite nests |
| 21. | Toxification of soil      | Reduced by crop rotation  |

## CHAPTER II

### TREES, SOILS AND SOIL BIOLOGICAL PROCESSES

The title of this book invokes some major questions:

Do trees improve soil fertility? If so, what are the mechanisms involved and how can this knowledge be applied to benefit agricultural systems? Equally, possible deleterious effects of tree species on soil properties require detailed understanding.

This chapter reviews the current understanding of these tree-soil relationships across the spectrum of natural and managed systems. In Section 1, the beneficial and adverse effects of trees on soil are broadly discussed. Practical systems of land use and management by which the said benefits of trees on soils may be implemented are also outlined. These will be detailed further in Chapter V.

It is suggested by J Anderson in section 2 of this Chapter that the development of improved management practices in agriculture using trees should be based on an understanding of the mechanisms by which the productivity of natural forest systems is maintained. In this light, the mechanisms of the efficient nutrient cycles in such natural systems, with particular reference to the effect of disturbance on nutrient retention by the system are outlined. The application of these concepts is then discussed with respect to the significant role of trees in agroforestry systems in improving soil fertility.

In section 3, M J Swift explains that the lack of understanding of the mechanisms described in section 2 precludes the adoption of standard practices by which trees could ameliorate soils. The relationships between the biological processes of litter decomposition, humus synthesis and humus breakdown are reviewed. The influence of trees on these processes should be a basis for soil amelioration.

The need for further investigation concerning the links between plant inputs, soil organic matter status, soil biological processes and soil fertility is emphasised throughout this chapter as an essential prerequisite to efficient management practices.

## 1. EFFECTS OF TREES ON SOILS

ANTHONY YOUNG

International Council for Research in Agroforestry

### SUMMARY

1. Land use systems in which effects of trees on soils play an important part are protective forestry, reclamation forestry (of eroded or salinized land or moving sands), production forestry, agroforestry and applications of these in watershed management.
2. There are some 20 distinct agroforestry practices, defined as arrangements of trees and herbaceous components in time and space.
3. Eleven processes are listed by which trees may improve soils, not all of which are proven.
4. A computerised model, Soil Changes Under Agroforestry (SCUAF), indicates a potential for agroforestry to achieve a steady state of soil fertility under productive use; some critical assumptions in the model require experimental testing.

### INTRODUCTION

This book has its origins in the basic concept of the Tropical Soil Biology and Fertility programme (TSBF) : that it is possible to maintain or improve the fertility of tropical soils through the manipulation of soil biological processes. Such a concept can only be achieved through two stages:

i A basic understanding of how soil biological processes operate, and what is their influence on fertility.

ii. The identification of practical management methods by means of which soil biological processes can be manipulated in such a way as to improve fertility.

It was out of discussions of the second stage, the realistic management options, that the present book arose. It was recognized on the one hand, that trees have certain distinctive effects on soils, many of them favourable; and on the other, that there were many circumstances in which land use systems that involve the planting of trees are practicable — not only technically, but also economically and from a social viewpoint. (Swift, 1984; Commonwealth Science Council, 1985; Swift, 1985).

The papers which follow contain discussions of many aspects of the ways in which trees affect soils. The task of this introductory review is to set these detailed aspects into perspective, by an overview of how trees achieve the desired beneficial effects, and what are the practical land use and management systems by which this can be brought about.

The following factors show that trees can be expected to improve soils:

- i. The soil that develops under natural woodland or forest, the classic brown earth of temperate regions, red earth of the tropics, is fertile. It is well-structured, has good moisture-holding capacity, is resistant to erosion and possesses a store of fertility in the nutrients bound up in organic molecules. This mature soil is the result of plant succession, with its associated soil changes.
- ii. In shifting cultivation, we have a demonstration of the capacity of forest to restore fertility. Nowadays, this practice is often thought of as environmentally undesirable, and certainly this is so once population increase has forced the shortening of the fallows. But formerly, shifting cultivation had something of a good name, as a way of letting the natural ecosystem restore what agriculture in the tropics inevitably (or so it was supposed) removed.
- iii. The cycles of carbon and the major nutrients under natural ecosystems have been demonstrated, most notably in rain forest but also in savanna and semi-arid ecosystems. So also has the often substantial nitrogen-fixing power of leguminous trees and certain other species. That is, not only can we observe that trees in fact improve soils, but to some extent, we know the details of how they do it.
- iv. Finally, in these background considerations, we have so often observed the adverse effects that follow forest clearance, the almost invariable decline in soil fertility, and sometimes the less easily reversible consequences of erosion.

#### SYSTEMS OF LAND USE AND MANAGEMENT

What are the practical systems of land use and management in which the planting and tending of trees, at least in part with a view to their effects on soils, play a part? These include the following:

- i. **Protective forestry:** the protection of sloping or other environmentally sensitive land by preservation of its natural forest cover, or upgrading of such cover where it is partially degraded. There may be multiple outputs - water, wildlife conservation and recreation.
- ii. **Reclamation forestry:** the reclamation of eroded, salinized or other degraded land by afforestation. The reclamation process can be followed by agroforestry, through a combination of productive use with maintenance of the improved soil conditions.
- iii. **Production forestry:** forestry, of which the primary aim is timber or fuel wood production, but in which soil amelioration is either an explicit secondary aim or at least a management requirement.
- iv. **Agroforestry.** This refers to a range of land use practices in which trees are grown in association with agricultural crops or pastures, and in which there is both an economic and an ecological interaction between the tree and non-tree components. A critical part of this definition, and that which distinguishes it from social forestry, is the existence of ecological interactions between the trees and other components, interactions which take place through the medium of microclimate or, our present concern, soils. Most agroforestry is social forestry, that is, forestry carried out the village or farm woodlots which, if they

are managed only with the aim of maximizing wood production, is not agroforestry. Agroforestry is not one kind of land use but a collective name of a wide range of practices.

v. Watershed management: land use planning which takes the watershed as the spatial unit, and which is particularly concerned with soil and water conservation. This is of a different nature, since it frequently involves any or all of the land use practices i-iv above. It is mentioned as a type of planning framework which makes much use of the effects of trees on soils.

### **THE RANGE OF AGROFORESTRY PRACTICES**

Agroforestry is not one kind of land use by a collective name for a wide range of practices. Three terms may be defined.

Agroforestry components consist of trees (including shrubs), agricultural crops, pastures, livestock and occasionally other components. To qualify as agroforestry, the tree component must always be present.

Agroforestry practices consist of arrangements of agroforestry components in space and/or time.

Agroforestry systems are specific examples of agroforestry practices, as found in a particular area. They are defined by such details as the tree and non-tree species, management practices, outputs (production and service), and the social and economic functions of the systems.

### **POSSIBLE ADVERSE EFFECTS**

It would be a biased unscientific view if the possible adverse effects of trees on soil were to be ignored. Some possible effects of this kind are as follows:

i. Nutrient loss, resulting from whole-tree harvesting, with possible adverse effects on second-cycle plantation forestry. This is a matter of concern to foresters, and raises the question of forest fertilization. The better the management, the greater the problem becomes at first sight, since with a faster annual increment, a greater volume of nutrients is removed at harvest. Litter fall and root growth may compensate.

ii. Moisture depletion. Some species of eucalypts have been blamed for desiccating the soil; and, an earlier point of debate, afforestation of reservoir catchments can in some circumstances reduce total water yield, despite regularizing flow. These are controversies on which firm views are held, and I shall refrain from comment.

iii. Soil erosion. A badly-managed forest can lead to accelerated erosion, as in the case of some teak plantations on sloping land. It should also be made clear that agroforestry does not necessarily conserve the soil; wrongly sited or poorly managed, it can be just as destructive as other land use systems.

iv. Adverse chemical and biological effects. Under this heading are grouped together such aspects as acidification by pine litter, or allelopathic effects of substances from litter or roots.

### **HOW DOES THE TREE DO IT?**

What are the mechanisms by which the generally favourable effects of trees upon soils are achieved? Some are well proven, some reasonable supposition; and among the latter are numbered some of the hypotheses of the TSBF. The processes listed are either experimentally demonstrated or widely accepted, except where otherwise indicated.

#### **Processes which augment additions to the soil:**

1. Photosynthesis: fixation of atmospheric carbon and its transfer to the soil.
2. Nitrogen fixation, both symbiotic and non-symbiotic.
3. Nutrient retrieval: the taking up of nutrients released by rock weathering in deeper layers of the soil, and their release by litter decay on the surface (not specifically demonstrated).
4. Providing favourable conditions for input of nutrients by rainfall and dust (not demonstrated).

#### **Processes which reduce losses from the soil, making the plant/soil system more closed:**

5. Protecting the soil from erosion (water and wind), thereby from loss of carbon and nutrients.
6. Trapping and recycling nutrients which would otherwise have been lost by leaching (not demonstrated).

#### **Improvement of soil fertility through physical conditions:**

7. Soils under trees generally have better physical conditions, including a higher water-holding capacity combined with good permeability and drainage, and greater erosion resistance, than non-forest soils.

#### **Processes which affect the quality of plant residues and the timing of their transfer to the soil:**

8. Promotion of a range of different qualities of plant litter, through supplying a mixture of wood and herbaceous litter (TSBF hypothesis).
9. Favourable effects of roots: growth-promoting substances in the rhizosphere (demonstrated in some cases) possibly also provision of a range of root-litter quality (TSBF hypothesis).
10. Timing of nutrient release. Under natural conditions, the provision of a steadily-decaying nutrient store in the form of soil organic matter. Under management, the potential to control timing further, e.g. through decisions on when to prune (basic TSBF hypothesis).
11. Effects of shading on microclimate, thereby on soil climate and rate of mineralization (demonstrated in some cases; TSBF hypothesis).

It is the last group of processes which is most fundamental to research in TSBF programme.

### **ORGANIC MATTER AND NUTRIENT CYCLING UNDER AGROFORESTRY: A COMPUTERIZED MODEL**

Turning from the broad viewpoint to the specific effects of agroforestry on soils, a computerized model has been developed at ICRAF. Called Soil Changes under Agroforestry, or the SCUAF model, it is at an early stage of development and has so far been applied only to the carbon and nitrogen cycles.

The long-term objective of the model is to have the capacity to forecast the effects on soils of a specified agroforestry system. However, at present we lack firm data on some of the critical assumptions about processes, and so there is a further immediate objective. This is to draw attention to what needs to be known if such forecasts are to be made with reasonable confidence; and thus to direct research into the determination of critical data.

The carbon and nutrient cycles are complex, and there have been a number of attempts to model them, particularly the nitrogen cycle. The model under agroforestry is essentially similar to that under a single ecosystem, except that there are two components, "trees" and "crops". The tree component normally leads to a net gain in carbon or nutrients, the crop component invariably to a loss. The two components may be combined in a time-based agroforestry system - a period of cropping followed by a planted tree fallow; or in a spatially-based system, a mixture of trees and crops.

The user specifies the type of agroforestry system, and the percentages of time, or space, under trees and under crops. He might then be asked to input all the numerous variables required to quantify the cycle. However, even the most comprehensive studies rarely cover all such data, and therefore use is made of a system of default values. The user inputs broad details of climate, soil and slope, and the model then assumes default values, including rates of growth, partitioning between different parts of the plant, rates of erosion and leaching, initial soil conditions, and assumptions about the manner of oxidation losses and other processes. The user is offered the opportunity to change any of these values.

Thus the inputs to the model are:

1. The physical environment.
2. The agroforestry system.
3. Initial soil conditions
4. Soil erosion.
5. Rates of plant growth: a. trees, b. crops.
6. Additions and removals by man (e.g. manure, fertilizer, crop harvest, crop residues, fuelwood harvest).
7. Assumptions about soil/plant processes.

The outputs from the model consist of tables and graphs showing changes in soil carbon and nitrogen with time. Examples of the carbon model are shown in Figure 1. Time-based systems show a dog-toothed graph, from the alternation of crops and trees, spatial systems a smooth curve. As the model is at present constructed, all systems show an approach towards an equilibrium value of soil

carbon. However, feedback interactions are being developed, for example an acceleration of the rate of erosion if soil organic matter is lowered, or a slowing of plant growth where nitrogen is depleted. This leads to the possibility of including a "catastrophe situation", in which the plant cover becomes so poor, and soil humus low, that the rate of erosion accelerates rapidly.

The exciting prospect is that it has been found possible, admittedly by making many untested assumptions, to develop an agroforestry system which on the one hand is productive, and on the other, leads to a steady state in the soil at an acceptable level of fertility, namely with humus content just over half that under natural forests; the net carbon loss under crops is balanced by an equal gain under trees. The assumptions and reasoning of this model are set out in Young (1985) and later in this book.

### EXAMPLES OF STUDIES OF THE EFFECTS OF TREES ON SOILS

Some references may be cited, to lend support to the points made above, and as an introduction to the kinds of studies on the effects of trees on soils that are available. This is necessarily a small selection from a substantial range of published results.

Among the many studies of nutrient cycling under rain forest, that of Golley et al. (1975) is one of the most thorough. The implications of the carbon and nitrogen cycles under forest for the design of agroforestry systems are discussed by Brunig and Sander (1983). Lundgren (1978) made a comprehensive comparison between nutrient cycling under natural forests and plantations in an area of highland Tanzania. There have been clear demonstrations of soil changes upon clearing forest for agriculture, such as that by Sanchez et al. (1983); an IBSRAM workshop on this subject was held in 1985.

As examples of work on the regenerative effects of forest fallows may be cited work by Toky and colleagues in north-eastern India, and current studies in Sri Lanka and Malaysia (Tokyo and Ramkrishnan, 1983; Andriessse and Schelhaas, 1985).

For nutrient cycling under plantation forestry, work on pine (Singh, 1982) and eucalypt (George, 1982; Turner and Lambert, 1983) may be cited, among many other studies. Chijoke (1980) compared the effects on soils of Gmeligna arborea and Pinus caribaea in six tropical countries. The effects of individual trees can be studied by taking soil transects from the base of the trunk to beyond the canopy (Kellman, 1980).

Among a range of FAO publications relevant to trees and soils, three of the Conservation Guides may be noted, those on watershed management, conservation in arid and semi-arid zones, and the environmental impact of forestry (FAO, 1976, 1977; Zimmerman, 1982).

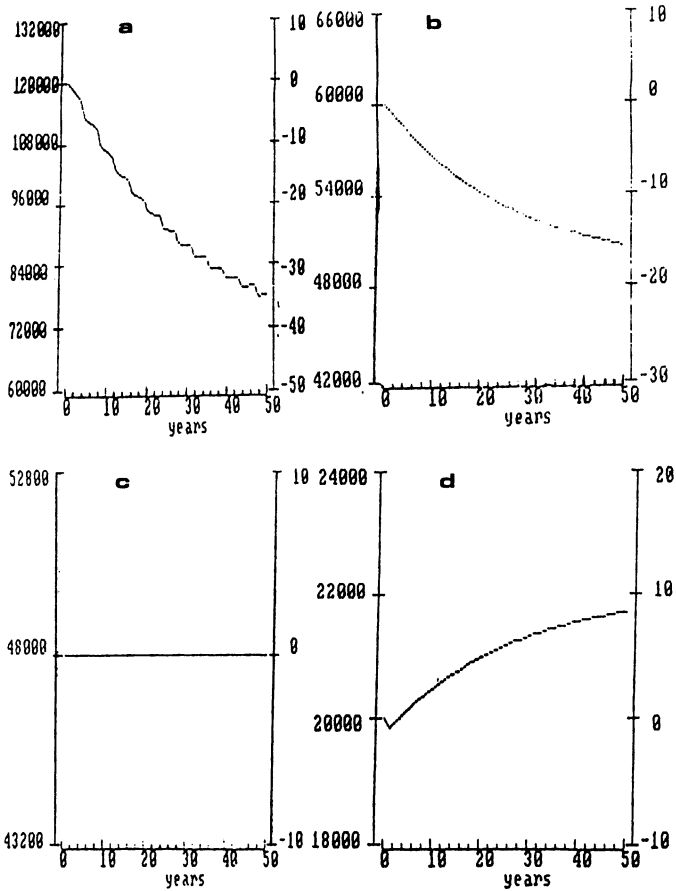


Figure 1  
Outputs from the ICRAF model. Soil Changes Under Agroforestry (SCUAF).  
The vertical axis shows soil humus carbon, kg/ha.  
a: humid climate, time-based system, 3 years crops, 3 years trees.  
b and c: humid climate, spatial system, 50-50% crops-trees, starting with different levels of soil carbon; c is a steady-state system.  
d: semi-arid climate, spatial system, 50-50% crops-trees, commencing on a degraded soil.

Starting points for the study of soil changes under agroforestry are the 23 papers in an ICRAF symposium (Mongi and Huxley, 1979) and the review of soil productivity aspects by Nair (1984). Nutrient cycling and the monitoring of soil changes are not included in agroforestry experimental work as often as they should be. Two examples of methods, and the kinds of result obtainable, are work on soil changes under alley cropping at IITA, Ibadan (Kang et al., (1981); and of nutrient cycling under coffee and cocoa in combination with shade trees in Costa Rica (Aranguren et al., 1982). The effects of agroforestry on soil conservation are reviewed by Wiersum (1984) and Lundgren and Nair (1985).

There is an annotated bibliography on nutrient cycling and organic matter relations of forests, with notes on almost 1000 studies, compiled by Adlard and Johnson (1983). A thorough review of the effects of agricultural tree crops on soils was made by Sanchez et al. (1984).

The ideas set out briefly in the present paper, and the implications for agroforestry of the TSBF hypotheses, are set out in more details in Chapter 6.

## **CONCLUSIONS**

A distinctive feature of land use systems which make use of trees is the potential to combine production with conservation. The production may be of goods or services, the goods including both wood and non-wood products. The services include shade, fencing, moisture conservation, wildlife conservation and recreation. Added to these is the service of conservation of resources, through protection against water and wind erosion, and the maintenance or improvement of soil fertility. This dual role, of production with conservation, applies whether the trees are part of forestry or agroforestry land use systems.

Some aspects of the favourable effects of trees on soils are well known, and what is required is the application of this knowledge through good land use planning and management. Other aspects, particularly some of the key relationships between tree litter and soil biological processes, require further research. If some of the basic hypotheses in this area can be proven, then there are considerable opportunities for applying such knowledge to practical land development, often with relatively low-cost inputs.

## **ACKNOWLEDGEMENT**

The SCUAF model for carbon and nitrogen cycling under agroforestry was developed jointly with Dr P M Hotten.

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## **2. PLANT NUTRIENT-USE EFFICIENCIES AND SOIL PROCESSES IN NATURAL AND AGRICULTURAL ECOSYSTEMS**

**J. M. ANDERSON**  
**Exeter University, U.K.**

### **SUMMARY**

1. Mechanisms of nutrient cycling in natural ecosystems are described with particular reference to the effect of disturbance on nutrient retention by the system.
2. The use of trees in agriculture is discussed as to its value in maintaining soil fertility in the conversion of forest to agriculture.
3. The application of these concepts is discussed with respect to the role of trees in agroforestry systems.

### **INTRODUCTION**

Adaptations of plant communities to nutrient-poor soils can be seen throughout the world but are particularly widespread in the tropics. Here over half of the region comprises highly weathered and leached soils (Oxisols and Ultisols) with available phosphorus concentrations usually well below those required for agricultural crops (Sanchez 1976). Yet some of the lowest fertile soils support rainforests of massive structure and productivity (Proctor et al 1983) as a consequence of tight nutrient cycling between vegetation and soil, and efficient production per unit of limiting nutrient (Vitousek 1984). This lack of correlation between forest structure and soil fertility has promulgated many disaster in agricultural development in the tropics where land cleared of forest has failed to sustain the expected crop yields, even with fertiliser inputs, or worse, has become catastrophically eroded.

In terms of plant-soil relationships it is therefore important to differentiate between the sustained production of unmanaged systems (which may be maintained on a finely balanced nutrient capital which is very sensitive to exploitation) and the sustained yield of cropping systems. Here the depletion of the nutrient capital, by product removal and periodic disturbance to the plant-soil linkage, must be balanced by nutrient returns and residue management to sustain soil structure. An understanding of the mechanisms by which the productivity of natural systems is maintained by highly efficient nutrient cycles and the responses of the systems to disturbance may provide the means to develop better management practices for agriculture and agroforestry in the humid tropics.

### **MECHANISMS OF NUTRIENT CONSERVATION**

A characteristic of most natural ecosystems, particularly forests, is that inputs of potentially limiting nutrients (NPK Ca and trace elements) in precipitation, weathering processes, by N fixation, and so forth are efficiently retained in soils and vegetation. The nutrient capital of the system therefore

increases with time until nutrient inputs and losses reach a semi-equilibrium state representing a small through-flow of nutrients in relation to the large internal pools and fluxes. Thus in most undisturbed forest ecosystems there are negligible losses of N and P or other limiting nutrients through leaching but considerable differences in internal nutrient pools and flux pathways according to nutrient availability on high and low fertility soils.

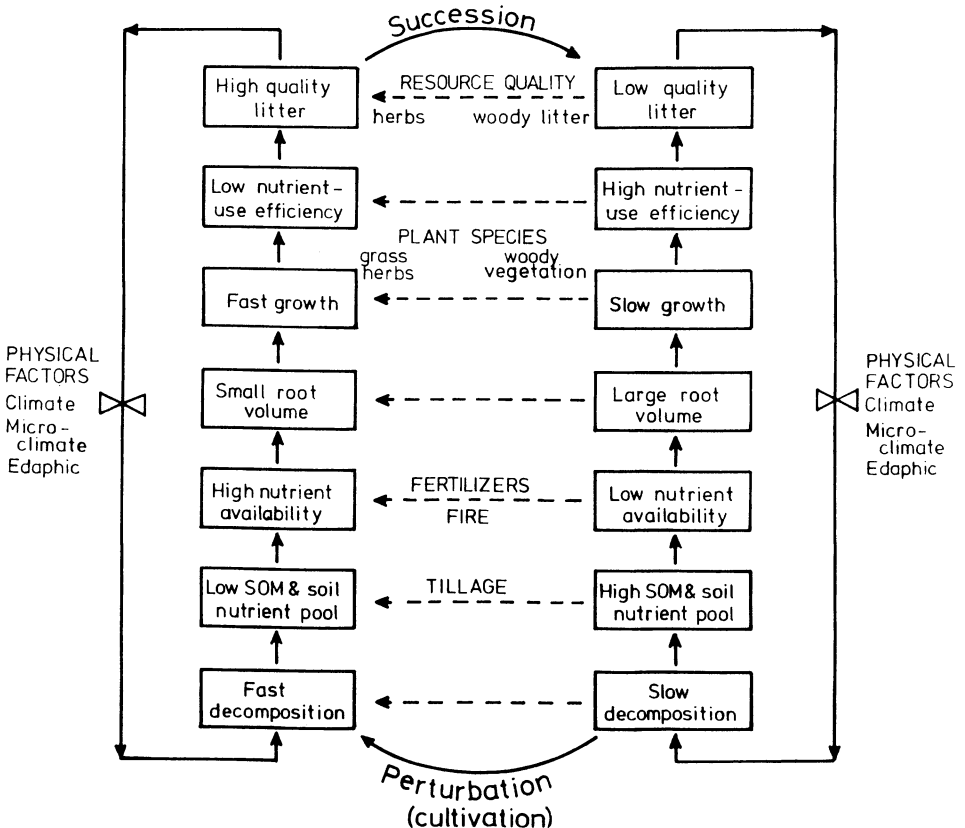
A key adaptation to nutrient limited conditions is the efficiency of nutrient use by plants since this influences the quality and quantity of resource inputs to the soil, decomposition processes and root biomass and distribution (Figure 1).

Variations in foliar concentrations of N and P according to soil nutrient availability is a generally observed phenomenon for natural vegetation and agricultural crops. If nutrient availability is high, fast-growing plants produce nutrient-rich litters which decompose rapidly (maize residues are a notable exception) and nutrient cycling between plant and soil is largely 'external' through the litter pathway. Vitousek (1984) has shown, however, that in forests on nutrient poor soils, the production of leaves or wood is more efficient per unit of N or P on nutrient poor soils than on high fertility soils. This is achieved by the selection of plant species which have low nutrient requirements, eg the N requirement of temperate deciduous forests is on average twice that of conifers in the same region (Cole and Rapp 1981). In addition, nutrients are translocated more efficiently from senescent tissues before abscission under nutrient limited conditions (Charley and Richards 1983). Evergreen, scleromorphic leaves are also associated with drought and/or nutrient stressed habitats. These leaves, which are long-lived, tough and insect resistant may be advantageous under conditions where their replacement is costly in terms of nutrients. Leaf longevity thus capitalises on photosynthetic returns over an extended time period on a 'high cost, slow profit' strategy since scleromorphic rain forest leaves have lower photosynthetic rates than plants on nutrient rich soils which operate on a fast turnover 'low cost, quick profit' strategy (Werger and Ellenbrook 1978).

The net result of the low nutrient concentrations in leaves and other tissues, and the efficiency of 'internal' nutrient recycling is that plant materials entering the decomposer sub-system have low resource quality (high lignin and low nutrient concentrations), slow decomposition rates and a high capacity to immobilize exogenous sources of nutrients. In some cases the litter quality of trees on nutrient-poor soils is so low that favourable environmental conditions for decomposition are overridden and organic soils form under tropical forests (Figure 2) This illustrates that the mechanisms exist, through selection of tree species, to increase the organic matter content of tropical soils to high levels. However, the soil physical and chemical properties associated with these extreme conditions, as in the heath forest soils of S.E. Asia, require considerable amendment to support nutrient-demanding, annual crops such as rice. Thus the effects of tree litter on soil properties are not necessarily consistent with sustained productivity.

Figure 1

Schematic representation of process controls and feedback mechanisms in plant-soil systems. Decomposition rates of litter, nutrient availability and hence litter quality have positive and negative feed-backs on nutrient cycles in high and low fertility soils respectively. Under extreme conditions, determined by the physical controls over decomposition interacting with litter quality, the high fertility system can degrade as soil organic matter is depleted; while in the low fertility system productivity declines as nutrients are immobilised in plant residues. Most natural systems undergo less extreme cyclical shifts in these plant-soil relationships. During plant community succession a more nutrient conservative (usually tree dominated) system develops while a major disturbance increases nutrient availability and shifts plant growth forms to the less mature phase (eg temporary cultivation). The various forms of disturbance associated with cultivation feed into the plant-soil cycle at different stages to initiate and reinforce the transition to an unstable, high nutrient availability agricultural system from a stable, natural system on low fertility soil.



Perhaps the most conspicuous adaptation of plants to nutrient poor soils is the production of a large root biomass which is usually concentrated on or near to the soil surface. The allocation of up to 70% net primary production below ground to maintain a high root: shoot biomass ratio is a characteristic of many tree species found on nutrient poor soils (Herman 1977) especially in savannas where both fire and water stress select for extensive rooting systems. This adaptation may be plastic, however, and both crop species and natural vegetation growing on a range of soil types have been found to allocate more photosynthate to root production with decreasing soil fertility (Wareing and Patrick 1975). An alternative explanation is that fine root turnover may be faster on high fertility soils (because of higher root resource quality and decomposition rates) and thus offset the low below-ground biomass values reported for these sites (Nadelhoffer et al 1985). A large perennial root biomass is highly effective in scavenging nutrients from dilute solutions, including canopy throughfall, especially in conjunction with mycorrhizas which are typically associated with roots on nutrient poor soils. The root mat is also a sink for nutrients released through wetting and drying of soils when the trees are dormant and integrates the uptake of nutrients released from litters decomposing at different rates on the forest floor. The efficacy of the root mat in preventing nutrient leaching is illustrated by studies in an Amazonic forest (Stark and Jordan 1978) where 99.9% of radioactive calcium and phosphorus added to the forest floor was absorbed or taken up by roots and only 0.1% of the activity was recorded below the rooting zone. Mineral-N is scavenged by roots with a similarly high efficiency and the soil water below the root mat in undisturbed forest usually contains very low concentrations of nitrate (Figure 3). In contrast, nitrate is very mobile in soils under arable agriculture and losses to the crop rooting system (other than through denitrification) are set by the depth of the wetting front in relation to rooting depth. Most nitrate is found in the top 15cm at the start of the rains in tropical agricultural soils and is leached down the profile at rates of about 0.5 mm mm<sup>-1</sup> rain in Alfisols and 1-5 mm mm<sup>-1</sup> rain in Ultisols.

Figure 2

Litter (o) and soil organic matter (●) standing crops in forest systems from the northern boreal region to the equator. Data for rain forests to the south of the equator are plotted the same degrees north. From Anderson and Swift (1983).

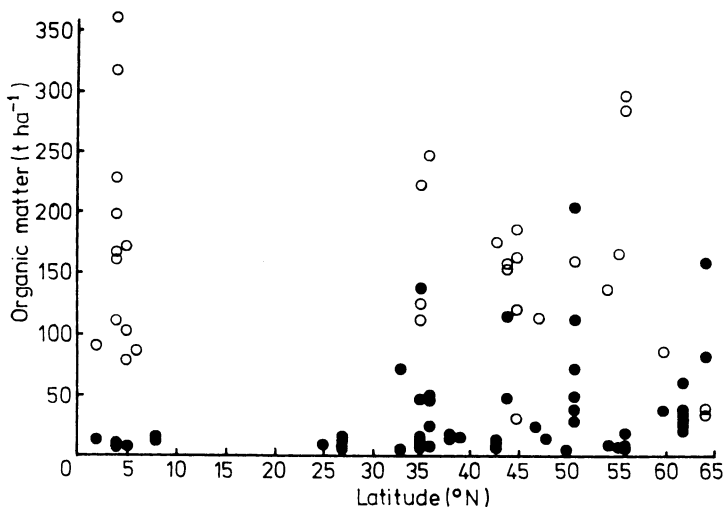
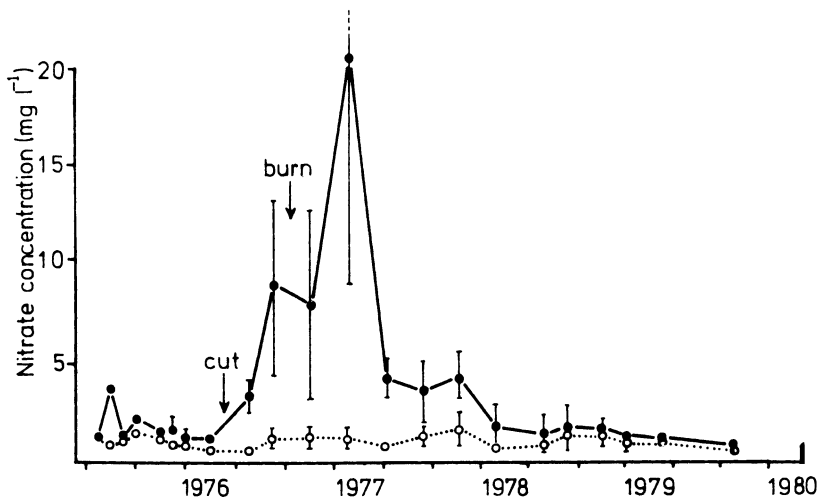


Figure 3

Nitrate concentrations (mean  $\pm$  95% confidence limits) in the soil water of a cut, burned and abandoned forest plot (o) and an undisturbed forest control (●) in the Amazon Territory of Venezuela. From Jordan (1985).



## EFFECTS OF PERTURBATIONS

The concept that the nutrient capital of ecosystems is conserved except during irregular periods of catastrophic perturbation, including fire and clear felling (Fig. 3), is generally supported by studies on forested catchments in temperate and tropical regions (Jordan et al 1972). Thus losses of nutrients from the system are generally negligible despite major storm events, individual tree falls and canopy defoliation by insects. This nutrient retention depends firstly upon the integrity of the plant-soil link or, if the rooting system is disrupted, upon the capacity of micro-organisms to immobilize nitrogen in resources, such as wood, with a high C : N ratio. But the local effects of the disturbance to vegetation cover may be to temporarily shift the nutrient dynamics of the system into a different mode: the changed soil microclimate and disrupted plant rooting systems result in enhanced nutrient availability to regrowth vegetation; litter resource quality is higher (higher nutrient concentrations and lower proportions of woody materials) and nutrient turnover is faster (Figure 1). The system reverts to a more conservative nutrient cycle as canopy closure is regained.

These shifts in the dynamic balance between nutrient immobilization and release in soils and vegetation are the basic mechanisms underpinning the practice of shifting cultivation in the tropics (Nye and Greenland 1964). When practiced on small plots with an adequate fallow period it is an ecologically sound analogue of gap phase regeneration and causes negligible nutrient losses to the forest ecosystem as a whole. But with increasing frequency or duration, area and intensity of disturbance, the regulatory mechanisms of nutrient conservation break down and the system inevitably degrades unless skillfully and intensively managed (Greenland 1975). The effects of frequent fires are particularly deleterious on acid soils. Burning increases the availability of P by raising the soil pH but it also converts Ca and K to soluble forms which are susceptible to leaching and depletes the nitrogen capital by nitrate leaching (Figure 3) and nitrogen volatilization. The loss of N through fires depends upon the proportion of biomass above and below ground exposed to the fire, the efficiency of the burn and the temperature of the fire (up to 70% N volatilised at 700°C). During an experimental burn of a secondary forest in Costa Rica, 30% of the initial amount of carbon in slash, 22% of the nitrogen and 49% of the sulphur were volatilised (Ewel et al 1981).

It is also well established that cultivation practices, and particularly mechanical tillage, result in a decline in the humus content of the soil. This is a consequence of changes in the soil thermal regime, disruption of soil aggregates and changes in the quality and quantity of plant residues returned to the soil (Swift and Sanchez 1984). Soil physical properties show a concomitant decline with humus content. The reduction in soil infiltrability is particularly marked in the conversion of forest to arable agriculture (Wilkinson and Aina 1976), Lal et al (1980) leaving the soils susceptible to surface run off and erosion. Aside from compaction from tillage operations, the decrease in soil faunal populations due to cultural practices is a major contributory factor to the changes in soil structure. Aina (1984) recorded equilibrium infiltration rates of 82  $\text{hr}^{-1}$  under forest fallow in Nigeria in contrast to 6  $\text{hr}^{-1}$  for adjacent plots which had been under continuous cassava cultivation for 12 years. Earthworm channels, with diameters up to 8 - 10 mm, and modal frequencies in the range 3 - 5 mm,

channels  $m^{-2}$  mainly in the 1 - 3 mm diameter range. Total porosity was 58% for the soils under forest and 38% for soils under cultivation with pores greater than 60  $\mu m$  (transmission pores) making up 35% and 10% of total porosities respectively.

The net result of perturbations to all the integrated components of the forest ecosystem is a precipitant shift from a high nutrient efficiency system to a low nutrient efficiency system with a massive loss of nutrient capital. The replacement system, under continuous cultivation, is maintained by high input/output fluxes in relation to the plan and soil nutrient pools and is thus inherently unstable. Productivity declines when the nutrient regime is insufficient to support the low nutrient-efficiency crop species and succession of wild species is prevented which can produce more biomass with fewer nutrients.

### THE AMELIORATIVE EFFECTS OF TREES

The restorative value of forest fallow is generally recognised and linked to the regrowth of deep rooted trees and shrubs, which recycle plant nutrients from considerable depth in the soil profile, and build up soil organic matter. During the fallow period, plant cover and litter protect the soil from the impact of raindrops, and the roots bind the soils, increase water infiltration and reduce run off and soil erosion. The shade conditions and surface litter cover also promote a diverse and active soil biota which maintain beneficial soil physical and chemical conditions. Most herbaceous crops are selected for their food and pest resistant properties and not for their nutrient use efficiency or ameliorative effects on soils. The replacement of forest by herbaceous species and the effect of the agricultural practices, positively reinforce the shift away from a balanced ecosystem. The incorporation of trees into agricultural systems, under the many agroforestry options, provides a means of capitalizing the food cropping potential of the fast cycling system and the stabilizing effects of perennials on soil properties and nutrient regeneration. The two main variants in agroforestry for continuous crop production are the simultaneous and sequential cropping systems.

In alley cropping, typically maize interspersed with Leucaena leucocephala or Gliricidia sepium hedges (Kang et al 1981), the two component systems are established simultaneously; though in these cases the tree produces a rapidly decaying nitrogen source and the maize residues form a low quality mulch.

The use of tree species which produce low quality litters as mulch, such as Acioa barterii, either for interspacing with Leucaena or cultivating with crops producing high quality residues which decompose rapidly, eg cowpea, provide further options for managing soil biological processes and nutrient recycling. Pilot studies suggest that maize yields, without fertilizers, can be doubled using N-fixing tree mulches with yields maintained under drought conditions. But the nutrient dynamics of these systems have not been studied in detail. In particular more information is needed on the phenology of the trees and crop plants in relation to spatial and temporal patterns of nutrient mineralization and uptake. In addition, studies on the root architecture of different species (how the soil volume is exploited horizontally and in depth) are critical for designing the optimum spacing and combinations of species for effective nutrient use and conservation.

Sequential cropping systems may follow a simulation of natural succession in which species which naturally follow intensive cultivation are replaced by

species with greater economic value. For example a cropping sequence might consist of (a) annuals and plants whose roots and stems are harvested (b) bananas and plantains (c) palms (d) cacao, rubber or commercial timber species (Jordan 1985). Thus the effects of nutrient-efficient species on soils are gained without a tree fallow.

Tree intercropping provides a permanent or transitional cropping system which is highly conservative of nutrients in the conversion of forest to agriculture. In this system the economically desirable crop is an understorey species (eg cacao) planted beneath larger trees, sometimes N fixers, which provide shade and sustain soil fertility through nutrient restoration by deep rooted species.

In conclusion, trees provide a means of manipulating both general and specific soil properties and processes in land reclamation, and in establishing sustainable agriculture for food, fodder and fuel. Improvements in soil fertility, and control of erosion and catchment hydrology are general benefits of re-forestation (with some exceptions). On the other hand the selection of particular trees species adapted to local soil conditions can be used:

- (i) to change the balance of cations returned to the soil surface in litter;
- (ii) to build up soil organic matter;
- (iii) to provide for fast or slow decomposing mulches to control nutrient release to crops and
- (iv) to enhance soil fauna activities (and hence soil physical properties). The manipulative potential of tree root systems has yet to be investigated.

It is, however, of central importance, in attempting to manage soil biological processes, to recognise the integrated nature of the plant-soil properties and that by altering one component variable, such as the elimination or addition of earthworms or changing litter quality, the whole system can shift its equilibrium state over a period of time.

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**3. INTEGRATION OF NUTRIENT CYCLING IN THE PLANT-SOIL SYSTEM;  
THE ROLE OF BIOLOGICAL PROCESSES**

**M. J. SWIFT**

**University of Zimbabwe, Harare**

**(IUBS/UNESCO : Tropical Soil Biology and Fertility Project)**

**SUMMARY**

The relationship between the biological processes of litter decomposition, humus synthesis and humus breakdown are reviewed. The possible influence of trees on these processes is indicated as the basis for potential soil amelioration. The need for further research into the links between plant inputs (as above and below ground litter), soil organic matter status and soil fertility is emphasised.

**INTRODUCTION**

The objective of the Tropical Soil Biology and Fertility Project (TSBF) is "to determine the management options for improving tropical soil fertility through biological processes". This objective was formulated on the premise that the sustainable productivity of natural ecosystems is derived to an important extent from the biological processes of litter and soil such as those of decomposition and humus synthesis. Fertility is dependent not only on the maintenance of these activities at certain critical levels but even more importantly on their functioning as an integrated system with regulatory mechanisms operating in a synchronised manner.

Whilst relatively closed and integrated soil systems may be characteristic of natural ecosystems, man's activities often have the effect of uncoupling them. The end-effects of this disruption have been extensively catalogued but there is very little information on the operation of the processes at a mechanistic level. This lack of understanding at a fundamental ecological level means that we have very little predictive capacity about the quantitative effects of these practices. Even more worrying is our inability to predict the functional mechanisms of potentially ameliorative practices. Among these, the planting of trees on degraded or 'problem' soils is a commonly advocated practice. It is an act of faith that trees have beneficial effects and that their presence results in restored or improved fertility. Little, however, is known of the mechanism of these effects. To enable the adoption of sensible policies for soil amelioration, we must be able to fit tree species with soil type and condition for a given climatic zone and have a good probability of predicting the outcome in terms of changed soil conditions. This we are unable to do under current lack of mechanistic insight.

The TSBF project has proposed a research methodology for examining some of the key questions concerning the integrated functioning of the soil system. Some of these ideas will be outlined here with specific reference to the potential ameliorative effects of trees.

### THE SOIL SYSTEM

One way in which biological processes in the soil can be seen operating as an integrated system is in relation to the flux of mineral nutrient elements. A relatively simple version of such a nutrient cycling model is given in Fig 1. The diagram may be made more explicit by detailing the biochemical processes and the groups of organisms involved. Three processes may be selected for particular attention however, those of litter decomposition, soil organic matter (SOM) formation and SOM decomposition. These processes are general, and crucial to the integrated cycling of key elements such as N, P and S in all soils. Equally significantly they are also potentially accessible to management.

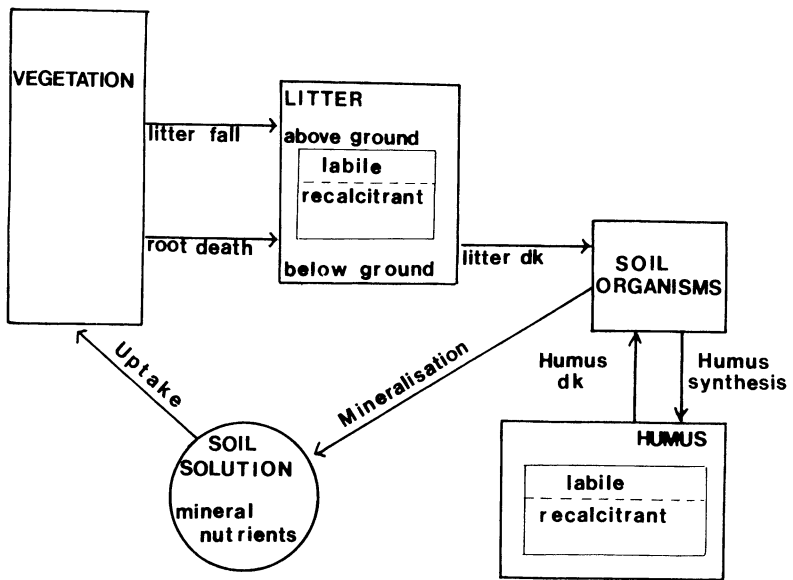


Figure 1: Integrated nutrient cycling in the plant-litter-soil system. The diagram shows some of the main processes influencing the flux of nutrients between plant and soil.

### LITTER DECOMPOSITION

The rate of decomposition of any litter component (or resource) has been described as being regulated by three categories of factor, the physical environment (P), the resource quality (Q) and the community of decomposer organisms (O), (Swift, Heal & Anderson, 1979). These factors operate interactively in a complex manner but can be pictured as a hierarchy (Fig 2).

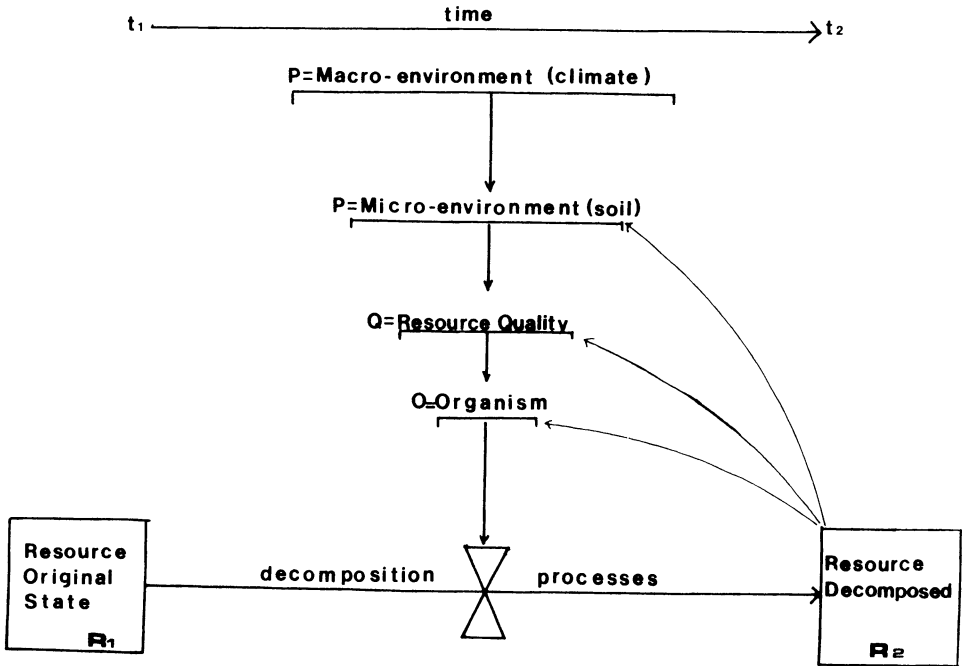


Figure 2: Regulation of the processes of decomposition. The processes of decomposition are pictured as being influenced by three groups of regulatory factors; O, the organisms of the decomposer community; Q, the quality of the organic matter (resource) being decomposed; and P, the physical environment. Although these factors are arranged in an hierarchy, feedback interactions also occur.

The overall limits to the decomposition rate are set by the climate of the region, in particular in the tropics by the rainfall period. These limits may be narrowed by specific micro-environmental (including edaphic) factors. Within this matrix of environmental determination the actual rate of decay of the resource will be determined by its intrinsic character - its resource quality. Even within the same environment, resources decay at widely varying rates (Table 1). The characteristics determining this are complex but are thought to include nutrient content, degree of lignification and the presence or absence of allelopathic molecules. Crudely speaking low quality (slow decomposing) litters are characterised by low N and P and high lignin; high-Q by high N and P and low lignin. All these factors influence the activity of the decomposer organisms. A final regulatory influence, still further narrowing the limits established by P and Q, may thus be the composition and/or biomass of the decomposer community (Anderson, Leonard, Ineson and Huish, 1985; Swift and Heal 1986 in press).

TABLE 1: The influence of resource quality on rate of decomposition. Calculated times for 95% weight loss for different litter components in a rainforest in Panama (Healy & Swift unpublished date)

- (a) Main litter components - calculated from Litter Fall to Standing Crop ratios (yrs).

<b>Fruit</b>	<b>Leaf</b>	<b>Palmfrond</b>	<b>Twigs</b>	<b>Branches</b>
0,3	1,2	1,9	5,6	19,4

- (b) Different leaf species - calculated from observed decay results in coarse mesh litter bags (months)

<u>Quararibea</u>	<u>Gustavia</u>	<u>Anacardium</u>	<u>Miconia</u>	<u>Oenocarpus*</u>
<u>Asterolepis</u>	<u>superba</u>	<u>excelsum</u>	<u>argentea</u>	<u>panamanus</u>
2,3	4,7	7,4	9,8	12,1

\*lamina of palmfrond

This simple model can be placed within the context of soil amelioration. In the conditions addressed here the soil environment may be extreme and will operate as a severely limiting factor within the hierarchy. An extreme example of this is the sodic or alkaline soil conditions described by Khanduja (Chapter 3) and Abrol (Chapter 3). Lowered fertility due to nutrient loss and/or development of low pH are equally relevant and more general examples however.

If amelioration of these soils by the use of trees can be achieved through the agency of decomposition processes, then it must operate not only by a direct effect on soil but through its influence on the quality and on organism variables which lie below the edaphic environment in the hierarchy. Q and O effects will

have subsequent feed-back to influence the edaphic environment (Fig 2) and it may be hypothesised that these are the pathways of amelioration. Trees influence the soil they are growing in by changing its microclimate and moisture regime, litter and soil organic matter both being mediators of these effects. The presence of trees also changes the context of decomposition processes. This can perhaps best be illustrated by considering an agro-sylvicultural system (such as alley cropping) in comparison with a monocultural crop as illustrated by Young and by Bashir Jama et al in Chapter 5.

The litter characteristics of the two systems differ greatly; the introduction of trees is likely to increase the amount of litter, particularly the below-ground litter due to perennial root systems; lengthen the time period of litter input; and in particular, widen the spectrum of resource quality. Whilst a monoculture crop will generally have only a few types of resource differing only marginally in their decay rates, trees produce twigs, branches and leaves (and perhaps woody or fleshy fruits) and fine and woody roots. It has been hypothesised in the TSBF proposals that this situation will tend to stabilise nutrient cycling in the soil with a consequent increase in sustainable fertility (Swift 1984, 1985).

The improved physical condition of the soil due to the presence of trees will also affect the nature of the decomposer community. Such changes can be described in general population terms but the influence of such changes on patterns of nutrient cycling remains to be determined (Lavelle 1983, 1984).

Changes in the patterns of nutrient cycling through the litter component are expected to take place in degraded or overcultivated soils under the influence of trees. These are hypothesised to be a progressive change from an open (leaky) system with a relatively few dominant pathways of nutrient flux to a more complex, integrated and consequently closed (tight) nutrient cycling systems.

With respect to potential for management of the system, the best option seems to lie in manipulation of the composition, timing and location of the litter inputs. This can be done by choice of appropriate tree species, including mixtures, and their management practices (e.g. pruning, lopping, biomass transfer).

### SOIL ORGANIC MATTER

Although exceptions can be advanced for specific soil types under particular conditions, sustainable fertility is generally supposed to relate closely to the equilibrium level of organic matter found in a soil. The commonly listed beneficial influences of soil organic matter (SOM) include improved soil aggregation and stability, increased water holding capacity, increased cation exchange capacity, decreased fixation of P, and increased content of organic N, P and S. SOM also stabilises nutrient cycling in a manner analogous to low-Q litters by acting as a 'slow release' reservoir of these elements. Despite these commonly perceived benefits, it is difficult to postulate a clear quantitative relationship between SOM content and the productivity of soil as this appears to vary in relation to other features of the soil. Indeed SOM content is a highly variable feature of soils as Sanchez, Gichuru and Katz (1982) have shown. Whilst major soil groups may show characteristic ranges, there is considerable variation within each group. This analysis confirms those of earlier authors (e.g. Birch and

Friend, 1956; Smith, Samuels and Cermuda 1951) on showing that there is little substance to the commonly advanced generalisation that the organic content of a tropical soil is necessarily lower than that of a comparable temperate soil.

The idea that tropical soils should have low organic contents is based on the perception that rates of organic matter decomposition are higher under the hot wet conditions characteristic of these regions. Certainly the rate of decline in SOM content under cultivation is high in the tropics but it was pointed out many years ago by Greenland and Nye (1959) that in assessing the standing stock of humus, consideration must be given to rates of synthesis as well as rates of breakdown. Both of these factors are thought to be very substantially affected by the vegetational cover. Young (1985 and Chapters 1 & 5) has made this the basis of his predictive model for soil organic matter content under different cropping and vegetational regimes. It is appropriate therefore to briefly consider the mechanisms of both processes.

### **(i) Humus Decomposition**

Lack of specific insight into the chemical structure of humus has resulted in little progress being made in the definition of mechanisms of breakdown. As a general proposition, however, it could be assumed that this is under the regulatory influence of the same set of factors as plant litter (Fig 2). With regard to climatic variables there is little doubt that this is so; the temperature and moisture regime and access to oxygen are all regarded as features influencing the rate of breakdown of humus. The existence of a quality spectrum in soil organic matter is also implicit in most recent models of SOM dynamics. At least two fractions are commonly recognised; a labile fraction which may be substantially decomposed in periods ranging from a year to a decade or two, and a recalcitrant fraction which may persist for many hundreds of years (e.g. see Van Veen, Ladd and Frissel, 1984). The rate of breakdown of each of these components may be further affected by physical complexing with clays. The implication is that components of humus have different chemical and physical properties which determine their rate of decomposition, which can be regarded as analogous to the concept of resource quality as applied to litter. Unfortunately the ability to fractionate SOM is at present very limited, as is the chemical definition of the different fractions. Thus it is not clear whether the existence of only two fractions is sufficiently explicit to predict SOM turnover. Nor is it certain whether it is justifiable to describe the two fractions from different soils as directly equivalent.

Nonetheless it is possible to hypothesise a two stage process of SOM decline during degradation of soil condition; first that the rate of humus decomposition increases due to changes in physical conditions and that this decline is due to breakdown of the more labile fractions; and thence secondly that the resultant equilibrium level is less diverse in fractional quality and is dominated by the most refractory components. This might result in a substantial decrease in the capacity of the SOM to serve as a nutrient source i.e. the decline in fertility will be greater than is signalled by change in total content alone.

Restoration of the quantity and quality of SOM is thus dependent on increasing the rate of SOM synthesis.

### Humus synthesis

The mechanisms proposed for humus synthesis can broadly be grouped into two categories. The first group of theories proposes that humus molecules are synthesised directly from the breakdown products of litter decomposition; alternatively it is postulated that there is a more distant relationship between litter decomposition and humus synthesis. This latter set of theories suggests that microbial catabolism of plant molecules is more complete and that the precursors of humus are products of microbial anabolism with melanin synthesis being a pathway of particular importance (see Hayes and Swift 1978; Stevenson 1982 for general accounts). It is entirely possible of course that both processes occur but whatever the specific pathway, humus synthesis may rightly be regarded as a by-product of litter decomposition. It is energetically fuelled by the catabolic activities of decomposition and irrespective of whether decomposition products are direct precursors of humus or not, their constituent elements certainly are, as incorporation experiments demonstrate. For instance Mayaudon and Simonart (1959a, b) have shown that <sup>14</sup>C from materials such as cellulose and lignin is incorporated in humus molecules within 30 days of addition of soil. The implication of fungi in humus synthesis makes it likely that there are microbial species common to the process of decomposition and humification. Unfortunately, however, there is little detailed information of this.

Thus the environmental and biotic context of humus synthesis may be the same as that of litter decomposition. It is a controversial question however as to whether there is a link between the quality factor in litter decomposition and that in humus formation. For instance, it is not known whether humus quantity and quality is related to the lignin content of the litter from which it is formed. Such evidence as exists is contradictory; it is most certainly, however, a question demanding further investigation.

In the present context, this question may be posed in the following form; whether the increase in SOM content observed under fallow (i.e. tree vegetation = Greenland & Nye 1959) is a product not only of the increased quantity of litter input but also of the broadened spectrum of resource quality.

### CONCLUSIONS

There seems to be good evidence that the presence of trees promotes the development of tight nutrient cycling regimes in soil. This ameliorative influence is effected through a number of mechanisms. These include; changes in the soil environment (i.e. water regime, texture, thermal and gaseous properties) that favour satisfied nutrient cycles; and direct quantitative and qualitative alterations to the bio-chemical pathways of nutrient cycling associated with changes in the microfloral and faunistic composition of the soil community. Each of these effects relates in some way to the organic status of the soil which is fuelled by the plant litter input. It is therefore proposed that the patterns and rates of litter decomposition should be an important focus of research in any attempt to determine the mechanisms for the ameliorative effects of trees on soil. It is moreover clear that in this respect the below-ground (i.e. root) input of litter warrants special attention both because it is ever-present in the system and because so little is known of its particular role.

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### **CHAPTER III**

#### **PROBLEM SOILS AND THEIR AMELIORATION BY TREES**

This chapter concentrates on the characterisation of some specific problem soils, the potential for amelioration of these soils by trees, and the extent to which it has been shown that trees can and do improve the fertility of these problem soils, thereby rendering them more agriculturally productive.

## 1. SOIL AMELIORATION PROBLEMS OF 'BRIS'

### SANDY SOIL IN PENINSULAR MALAYSIA

A. B. OTHMAN

Malaysian Agricultural Research and Development Institute, Malaysia

#### SUMMARY

1. Sandy 'Bris' soils are a problem soil on the sandy costal ridges of the eastern coast of Peninsular Malaysia.
2. They are regarded as 'problem' soils because of their low water and nutrient holding capacity.
3. Introduction of trees and crops could be a solution to this problem.
4. The soil requires a pretreatment before trees can be planted.

#### INTRODUCTION

Sandy beach deposits, locally termed as 'Bris' soils, have been categorised as problem soils. The soils described are developed on the sandy coastal ridges of the eastern coast of Peninsular Malaysia. Characterised by a sandy texture, these 'Bris' complexes occur as a narrow belt fringing the coastline varying in width between 200m and 6km from the coast. The total of 'Bris' soils in Malaysia is approximately 204,564 ha of which 16,464 ha. are found in Peninsular Malaysia (Wahab, 1982).

Lack of silt and clay in most of these soils render them very infertile in terms of plant nutrients. Additionally, their low water holding capacity results in extremely high irrigation costs for reasonable crop yields. Primarily for these reasons, agricultural planners have disregarded these soils for large scale agricultural development, and not much has been achieved in the improvement of the productivity of 'Bris' soils (Ibrahim, 1981).

Introduction of trees and crops that can be productive on 'Bris' soils seems one of the possible solutions to this long known problem of the 'Bris' area. This can be achieved by giving prime consideration to improving the agricultural technology in this area with specific emphasis on soil management techniques.

#### FORMATION OF SANDY DEPOSITS

The pattern of soils forming the 'Bris' complex indicates that the soils of beach ridges and swales are of recent age while on old beach ridges of subrecent age. They are formed by a northward longshore littoral drift, periodically influenced by heavy seas during the monsoon that is between August and December.

The soils developed on the 'Bris' complex range from Brown sands to Podsolis with transitional groups showing varying degrees of podsolization. In Peninsular Malaysia the 'Bris' soils have the following sequence. Baging series

(Typic Quartzipsamment) of recent marine sand deposits in which there are few or no weatherable minerals, followed by Rusila series (Typic Tropquad), a soil occurring in depressional areas and typically possessing considerable amounts of organic matter at the soil surface; Rudua series (Typic Tropohumud), a ridge sloping soil, and Jambu series (Arenic Tropohumod), a ridge top soil are morphologically similar, but spodic horizons occur at different depths. Rudua has a spodic horizon occurring within 1 m while the Jambu occurs below 1 m.

### THE AMELIORATION ASPECTS

The 'Bris' soils are characterised by brown sands. The mineral component is of essentially granular quartz grains. Particle size distribution indicates that the soil contains more than 90% of total sand.

Moisture content by weight for the 'Bris' soils showed that the range of available water in the surface soil is between 0.04 to 0.06 cm cm<sup>-1</sup>, and this indicates that the soil has very low water storage capacity (Othman, 1985). During prolonged dry conditions, 'Bris' soils create a condition similar to that of the drought-prone semi-arid regions of the world, particularly during the months between January and April. This is because of the low water retaining capacity and extremely high infiltration rates. The resultant problems of 'Bris' soil are water holding capacity and nutrient holding capacity. In addition to these, the 'Bris' soils also experience very high soil temperatures and this inhibits germination and retards crop growth. Fortunately the area under the 'Bris' have adequate rainfall, particularly during the wet monsoon season during which some areas in the east coast are completely inundated.

The most important considerations in ameliorating the 'Bris' soils for agriculture are the selection of crops which tolerate the drought conditions in the area and the build up of organic matter content to increase water and nutrient holding capacities. Some of the promising crops that have been cultivated are coconut, cashew, tobacco, watermelon, cabbage, passion fruit, and pigeon pea. Nevertheless, very high fertilizer input and adequate water supply are needed to obtain decent crop yields. Since large doses of fertilizer are necessary for the development of these areas, these beach soils have very low agricultural potential where these are not economically feasible.

Large areas of coconut palm have been planted on these soils but even with liberal doses of fertilizers their performance has been invariably poor. Leguminous crops grown with the idea of improving nutrient status and alleviating the drought conditions periodically experienced in these soils have performed poorly. This is due to poor water retention. Phenomenal infiltration rates in these soil profiles cause fertilizers to be leached out.

To develop these areas there is a need to increase micropores for greater water retention and to increase nutrient holding capacity. This could be achieved by introducing organic manures, composts, and mulches into the system because they provide:

1. organic matter which, according to Wong (1985), not only increases the chemical activities in the 'Bris' soils, but also helps to develop more favourable soil physical conditions for the trees (e.g. cashew, Pilus et al 1982) to grow. Organic matter content also indirectly controls the cation exchange capacity of the 'Bris' soils and increases soil biological activities.

It also thought to have contributed to observed differences in cashew growth performances. It has been confirmed by Pilus et al, (1982) that the amount and quality of organic matter have significant effects on the height as well as the canopy surface area of the cashew tree.

2. plant nutrients, and

3. help to reduce soil temperature. As reported by Wahab (1983), the surface soil temperature recorded at 2:00 pm showed that the temperature under mulching was 6°C lower than that where there was no mulching. The water should also be retained longer in the root zone in the presence of organic materials.

The above factors are of importance but the choice of tree/crop, the economic value of the tree/crop, and the interaction of smaller volumes of soil with organic matter and mulches must be considered in conjunction with these factors. Especially with tree crops where only the volume of soil within a restricted area such as a hole (within the effective rooting volume of the crop) needs to be improved. Trying to completely change the environment and condition of the soil would be extremely difficult and expensive, but partial change might achieve significant results. By the interaction of limited volumes of sand/organic matter mixtures and mulching materials to modify the water retention and transmission properties of the soil within the soil profile, economic costing would be achieved.

The question of the possible practical implications on the use of soil conditioners may be of special relevance on the 'Bris' soil in Malaysia particularly with respect to tree planting. Experimentation and critical economic evaluation is necessary and hopefully a preliminary report on the progress of this work will be published soon. However, an integrated, multidisciplinary approach is necessary, if the potential of soil conditioners are to be exploited. Such factors as irrigation system, drought resistance in plants, economic value of the crop, agronomic techniques designed to conserve on fertilizer usage in conjunction with the improvement of structure must be considered.

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## 2. SALT AFFECTED SOILS AND THEIR AMELIORATION THROUGH AFFORESTATION

H.S. GILL AND I.P. ABROL

Central Soil Salinity Research Institute, Karnal-132001, India

### SUMMARY

(1) The extent of the salt affected soils in India and salient characteristics of their broad categories are presented. Afforestation of these problematic soils is envisaged to be a promising land use.

(2) The successful establishment of selected tree plantations was achieved by a relatively easier and economical posthole technique compared to the usual methods of tree planting in an extremely alkali soil.

(3) Data on leaf litter production in a seven years old plantation of *Acacia nilotica* (L.) Willd. ex. Del. and *Eucalyptus tereticornis* Sm. grown on an alkali soil is presented.

(4) The ameliorative effect of the two plantations on the soil and micro-climate of a highly alkali soil at selected growth intervals is presented.

### INTRODUCTION

Excess salts reduce the productivity of an estimated 7 million ha of the otherwise productive soils in India (Abrol and Bhumbra, 1971). Based on geographical distribution, salt affected soils can be grouped as (i) salt affected soils of the coastal regions, 2.1 million ha; (ii) inland saline soils of the arid and semi-arid regions, 2.5 million ha; and (iii) alkali soils of the sub-humid regions in the Indo-Gangetic plains, 2.5 million ha. Salt affected soils are broadly classified into two categories depending on the nature of salts exerting a dominant influence on the soil properties and plant growth. These are: (i) saline and (ii) alkali soils. While neutral soluble salts consisting of chlorides and sulphates of sodium, magnesium and calcium exert a dominating influence on plant growth in saline soils, presence of sodium carbonate in small to appreciable quantities is responsible for building up excessive exchangeable sodium percentage (ESP) and high pH which in turn have an adverse effect on soil physical properties and plant growth in alkali soils. Apart from the soil characteristics and climatic features, the optimum methods of utilizing salt affected soils of an area depend on the nature and amounts of salts and their distribution in the soil profile.

Utilization of salt affected soils for afforestation appears a promising land use because of the increasing pressure on good soils for food production, fast exhaustion of firewood and timber resources and the need for healthy maintenance of an agro-ecological system. Management of these soils for successful afforestation requires amelioration of the limited root zone for initial establishment and rapid early growth. Thus, a special site preparation treatment is generally a must because tree planting procedures followed for the normal or good soils do not hold good for inhospitable sites (Abrol and Sandhu, 1981, Gill and Abrol, 1986 and Gill, 1986). Only a few efforts have been made

to afforest salt affected soils in the past (Yadav et al. 1972) and most of them were almost complete failures for want of scientifically evolved information. This poses a severe restriction on planning and planting operations. Therefore, field experiments were undertaken to work out a suitable technique for raising plantations of *Acacia nilotica* (L.) Willd. ex. Edl. and *Eucalyptus tereticornis* Sm. in highly alkali soils. Leaf litter production of the two plantations and their ameliorative effect on the soil and micro-climate were also estimated.

### SITE AND METHODS

A highly alkali site was selected for field investigation at an altitude of about 235 m in the Central Soil Salinity Research Institute's experimental farm at Gudha (76° 56'N, 29° 29'E) in the Karnal district of Haryana state. Salient physico-chemical characteristics of the experimental farm are included in Table 1. Soil samples were analyzed following standard procedures outlined by Jackson (1967).

TABLE 1. Important physico-chemical characteristics of a highly alkali experimental site.

Soil property	Soil profile horizon in cm					
	0-15	16-27	28-46	47-87	88-139	140-200
pH <sup>a</sup>	10.5	10.2	10.1	10.0	10.0	9.9
EC <sup>a</sup> (dSm <sup>-1</sup> )	3.98	1.76	1.04	1.12	0.96	0.62
Detritus (percent)	0.58	2.46	3.88	5.82	34.26	7.46
CaCO <sub>3</sub> Eq (%)	0.68	0.72	0.79	0.92	6.32	9.37
Sand (percent)	54	51	49	54	51	65
Silt (percent)	27	27	26	20	23	18
Clay (percent)	18	23	24	25	19	11
ESP <sup>b</sup>	96	97	98	96	92	72
Textural class	sil	sil	sil	CL	1	ls

- a. Measured after occasional shaking soil: water suspension in a ratio of 1:2 for half an hour.
- b. Exchangeable sodium percentage.

The selected site preparation techniques comprised planting of Eucalyptus tereticornis Sm. and Acacia nilotica (L.) Willd. ex. Del. in four differently dimensioned (dia. x depth) postholes and a pit dug out using soil augers and an assortment of spades and shovels respectively. Details of the dimensions of postholes and the pit and the quantity of amendments used for their refilling are given below:

Treatment	Dimensions (cm)	Volume (cm) <sup>3</sup>	Gypsum (kg)	FYM (kg)
T <sub>1</sub>	10 x 120	9425	3	4
T <sub>2</sub>	10 x 180	14137	3	6
T <sub>3</sub>	15 x 120	21206	3	8
T <sub>4</sub>	15 x 180	31809	3	12
T <sub>5</sub> Pit	90 x 90	572555	12	24

Given amounts of amendments were mixed with the original highly alkali soil used for refilling of the postholes and pit.

About six month old saplings of the two species were planted on July 17, 1979. The experiment was laid out in a Randomized Block Design layout and replicated four times. Each replicate sized 6 m x 6 m represents four plants with a spacing between the rows and plants of 3 m. Nitrogen (urea) was applied at the rate of 20 and 10 g N plant<sup>-1</sup> on Aug. 4 and Nov. 26 of 1979 respectively. Plants were watered on the need-felt basis until a year past planting. Percent survival and selected growth parameters were monitored. Acacia trees were lopped off the undesired branches 16 and 42 months after planting. The biomass lopped as foliage and woody matter is expressed on an oven dry basis.

#### Litter production

Irrespective of site preparation techniques the average leaf litter produced in Acacia and Eucalyptus plantations during July-August, September-October, November-December, January-February, March-April and May-June between July, 1982 and April 1985 was estimated by collection of foliage shed in containers, 120 cm long and 60 cm wide, in numbers sufficient to represent all the possible locations within their canopies. Amounts are expressed on an oven dry basis.

#### Ameliorative Effect

The ameliorative effect of Acacia and Eucalyptus plantations was evaluated by analyzing the soil samples of the profile (0-5, 6-15, 16-30, 31-45 and 46-60 cm) for pH, EC and organic carbon content in September of 1982 and 1984 besides at the planting time in 1979. Average water infiltration was also measured appropriately.

### Micro-climate Modification

During January 1982 to December 1984, the mean soil temperature at 5 and 20 cm depths and the mean air temperature (at 137 cm height from the ground surface) within the canopies of Eucalyptus and Acacia, and at similar locations on the neighbouring dummy bare land, was measured on 15th and 30th day of each month at 07:22 and 14:22 hours.

## RESULTS AND DISCUSSION

### Survival and Growth

The per cent survival and important growth parameters recorded 6 years after planting showed (Table 2) that the adopted methods of site preparation were equally good for the establishment of Acacia and Eucalyptus on a highly alkali soil. Average height of Eucalyptus and Acacia varied between 7.79 -9.20 m and 5.96 - 6.85 m respectively. Girth diameter at stump or 5 cm height (DSH) and at breast or 137 cm (DBH) height of Eucalyptus ranged between 13.4 to 16.5 cm and 8.9 to 11.5 cm respectively. Corresponding range of DSH and DBH for Acacia was 13.5 to 16.9 cm and 10.2 to 13.2 cm. Growth of both the species occurred at a rapid rate during the initial 2-3 years of planting. However growth was somewhat slow afterwards, particularly that of Eucalyptus. Acacia trees were noticed growing into a dense and lush green closed canopy whereas Eucalyptus exhibited limited growth of chlorotic looking foliage and widely open canopy even after 6 years of growth.

The results, thus, show that planting of the given two tree species in postholes with limited width but greater depth that were refilled with the original sodic soil mixed with limited quantities of amendments like gypsum and FYM, survived as well as in pits of comparatively large volume with high requirements for the amendments. This makes the posthole method of site preparation promising (Abrol and Sandhu, 1981; Gill and Abrol, 1986) because it is easier and more economical than the generally advocated (Pande, 1967; Yadav et al., 1972) pit technique. This new technique of site preparation also holds scope for mechanical adoption.

### Biomass Yield on Lopping of Acacia

Crown growth of Acacia was profuse unlike that of Eucalyptus throughout the observed growth period. Thus, to effect a proper balance between the trunk and crown of trees for their desired growth, undesirable shoots on stems were lopped to one-third of the height of Acacia trees 16 and 42 months after planting. This yielded considerable woody matter and foliage (Table 3).

TABLE 2: Effect of site preparation methods on survival and growth of the given trees after 6 years of planting  
 (DSH = Girth diameter at stump of 5cm height)  
 (DBH= Girth diameter at breast of 137cm height)

<u>Eucalyptus tereticornis Sm</u>				
Treatment	Per cent survival	Height (m)	DSH (cm)	DBH (cm)
T <sub>1</sub>	100	7.79	13.4	8.9
T <sub>2</sub>	100	8.29	15.1	10.4
T <sub>3</sub>	94	7.89	14.3	9.7
T <sub>4</sub>	100	8.46	15.8	10.9
T <sub>5</sub>	94	9.20	16.5	11.5
Mean	98	8.33	15.0	10.3
LDS (0.05)	NS	NS	NS	NS
<u>Acacia nilotica (L.) Willd. ex Del</u>				
Treatment	Per cent survival	Height (m)	DSH (cm)	DBH (cm)
T <sub>1</sub>	100	5.96	13.5	10.2
T <sub>2</sub>	100	6.39	14.4	11.1
T <sub>3</sub>	100	6.47	14.5	11.1
T <sub>4</sub>	100	6.47	15.9	12.4
T <sub>5</sub>	100	6.85	16.9	13.2
Mean	100	6.43	15.0	11.6
LDS (0.05)	NS	NS	NS	NS

TABLE 3: Biomass (kg ha<sup>-1</sup>) lopped from the tree bolls after 16(a) and 42(b) months of planting Acacia nilotica (L.) Willd. ex. Del.

Treatment	Woody matter			Foliage			Foliage + woody matter
	a	b	a+b	a	b	a+b	
T <sub>1</sub>	1662	3644	5306	565	1356	1921	7227
T <sub>2</sub>	1835	4427	6262	642	1681	2323	7943
T <sub>3</sub>	1874	3360	5234	676	1396	2072	6630
T <sub>4</sub>	2264	4333	6597	874	1698	2572	9169
T <sub>5</sub>	3015	4061	7616	1012	1816	2828	10444
Mean	2130	4073	6203	754	1589	2343	8283
LSD (0.05)	756	NS	NS	106	NS	NS	NS

The average total biomass yield of foliage and woody matter varied between 1921 - 2828 kg ha<sup>-1</sup> and 5306 - 7616 kg ha<sup>-1</sup> respectively from these loppings. This suggests that in alkali areas, Acacia may be a promising species for producing woody matter and foliage worthy of firewood and forage respectively. Because of its greater resilience, proper management of the Acacia plantation may be regulated for biomass production shortly after planting. Foliage of Acacia was analysed to be a rich source of crude protein and woody matter having significantly more firewood value than that of Eucalyptus (Gill, 1986).

#### Litter Production

The Acacia plantation was noted to produce markedly more foliage litter than that of Eucalyptus. Litter production in the Acacia plantation increased regularly with growth years. But it was not observed to be so in the case of Eucalyptus. Bimonthly distribution of litter produced in a year indicates (Table 4) that the winter season (Nov. - Feb.) accounts for more than 40 and 50 per cent of the total for Acacia and Eucalyptus respectively. Higher litter production by the Acacia than the Eucalyptus plantation results from the greater aerial growth of the former species.

The concentration of N, P, S, K and Mg in the litter of Acacia was notably higher than that of Eucalyptus. But the opposite was the case for Ca and Na. Concentration of these nutrients in general declined with the successive growth years. However, chemical composition of the litter produced during the given bimonthly span of 1982 to 1984 did not vary significantly. Such observations were also reported by Ghose et al. (1982). However, the amount of litter production is expected to vary greatly with the species, stocking rate and canopy growth as well as with the edaphic factors.

TABLE 4: Average litter production (Kg ha<sup>-1</sup>) during given time periods of 1982-1984 by the canopies of Eucalyptus tereticornis Sm and Acacia nilotica (L.) Willd. ex. Del.

Time period	<u>Eucalyptus</u>				<u>Acacia</u>			
	1982	1983	1984	Mean	1982	1983	1984	Mean
July - Aug.	148	152	132	144	252	465	552	423
Sept. - Oct.	165	178	184	176	218	326	386	310
Nov. - Dec.	252	234	262	249	924	1168	1494	1195
Jan. - Feb.	196	212	218	209	635	1096	1225	985
Mar. - April	152	166	180	166	292	378	516	370
May - June	114	132	126	124	216	416	678	462
Total	1027	1072	1102	1067	2537	3849	4851	3746
LSD (0.05)	122	111	136	124	346	208	414	285

#### Ameliorative Effect

The ameliorative effect of Acacia and Eucalyptus plantations on the soil properties was noted to be considerable. Both the soil pH and EC (Fig. 1) were found to be reduced. Reduction was more in the surface layer and it decreased with depth to almost negligible at 60 cm depth. The soil organic carbon content increased to about double the initial value with Eucalyptus. The increase was about three times under Acacia plantation. The effect of Acacia on the increase in soil organic matter content was notably more than that of Eucalyptus. However, both the species effected a similar change in the soil pH and EC. The greater increase in organic carbon of the soil under the Acacia plantation is ascribed to greater additions of litter to the soil. The water infiltration rates of the soil also (Fig. 2) improved with growth of Acacia and Eucalyptus plantations. These observations corroborate the findings of Vadiunina (1964).

#### Microclimate Modifications

The mean air temperature under the Acacia canopy was found to be lower by e to 5°C during summer and higher by 2 to 4°C during the winter than in the neighbouring open area. Similar observations were made in respect of the Eucalyptus canopy (Fig. 3) but the magnitude of the modifying effect was less than the canopy of Acacia. The influence of the two canopies on the thermal regime of the soil at 5 and 20 cm (Fig. 4) depths was also of the modifying type. Fluctuations were more marked for the soil temperature recorded at 5 than that at 20 cm depth in the open. Effect of tree plantations during the summer months was that of the blanketing type but it was of the sheltering type during the winter months. Tree plantation modified the thermal characteristics of the environment by their sheltering effect in cutting insolation and by their blanketing effect in restricting the outflow of heat thereby keeping the ground warmer during winter and cooler in the summer season.

Figure 1  
Changes in pH, soluble salts (EC) and organic carbon content of a highly alkali soil under Eucalyptus (a) and Acacia (b) plantations.

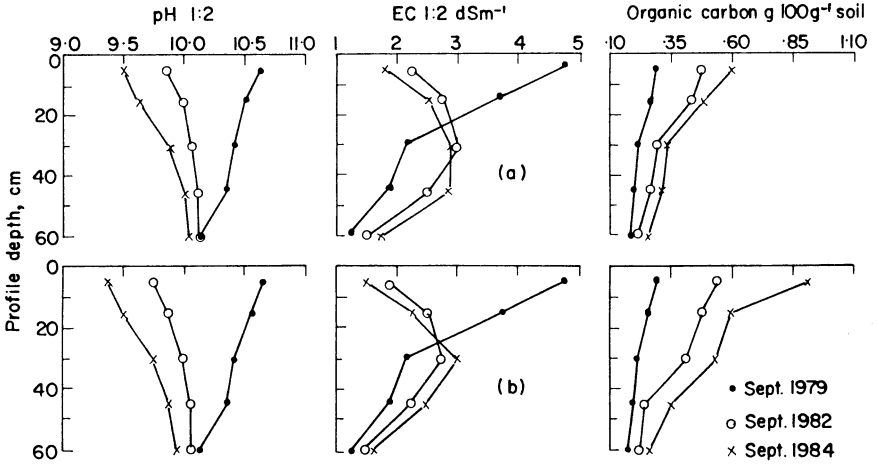


Figure 2  
Effect of Eucalyptus (a) and Acacia (b) plantations on cumulative infiltration of a highly alkali soil.

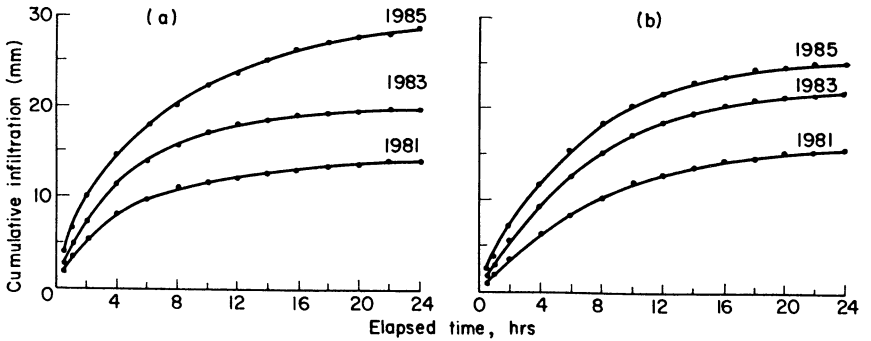


Figure 3  
Changes in atmospheric temperature in the open (.) and in canopies of Eucalyptus (o) and Acacia (x)

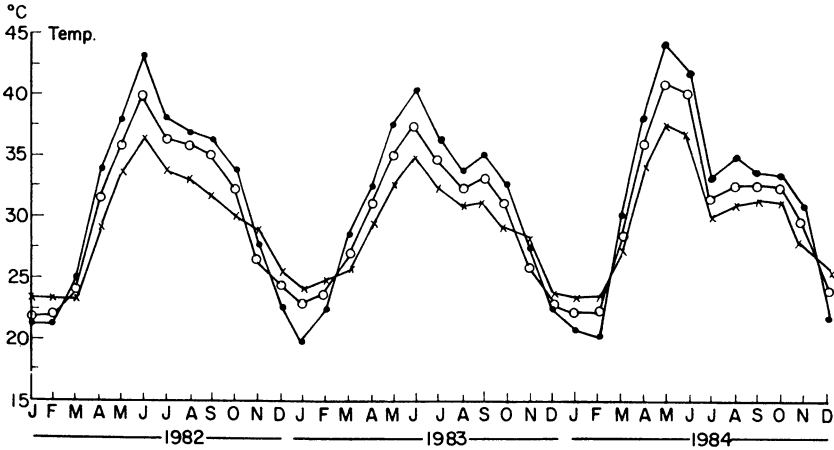
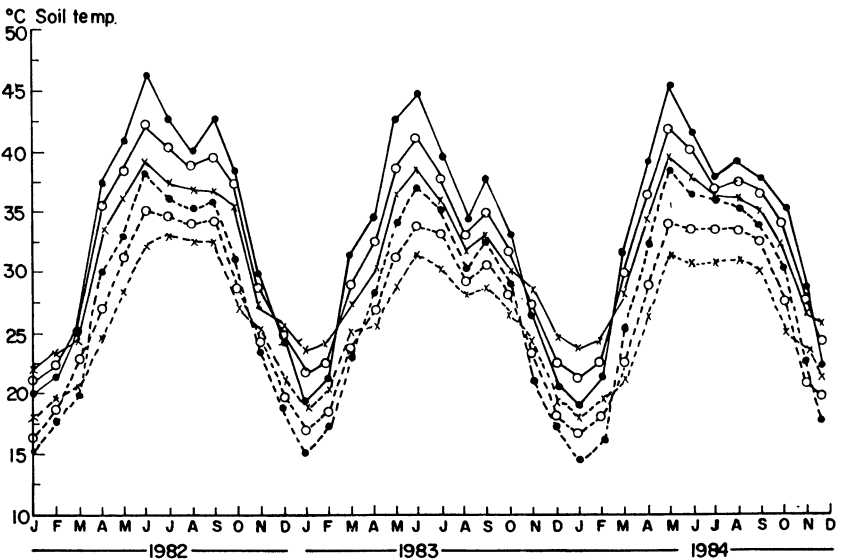


Figure 4  
Changes in soil temperature at 5 (-) and 20 (...) cm depths in the open and in canopies of Eucalyptus (o) and Acacia (x).



### **CONCLUSIONS**

The ameliorative effect on the soil of tree plantations is based on the penetration of strong roots, enrichment of the soil in humus and nutrient content through addition of organic substance from decomposed plant parts and on the improvement of N status of the soil through symbiotically fixed N in case of N fixing trees such as Acacia. Plantations also improve water intake rate of impermeable soils and thereby aid in the conservation of rain water which otherwise is lost as run-off.

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**3. UTILIZATION OF ALKALI SOILS IN THE PLAINS OF  
NORTHERN INDIA - A CASE STUDY**

**S.D. Khanduja,<sup>†</sup> V. Chandra, G.S. Srivastava,  
R.K. Jain, P.N. Misra and V.K. Garg**

**National Botanical Research Institute, Lucknow, India.**

**SUMMARY**

- (i) Investigations on the utilization of alkali soils without prior reclamation with chemical amendments conducted at Banthra Research Station for over 30 years are reviewed.
- (2) Plants of agricultural, horticultural and silvicultural interest, and also for woody biomass production, which are adaptive to alkali soils have been identified.
- (3) The ameliorative effect of tree canopy cover is reflected in reduced soil pH and exchangeable sodium, but increased organic carbon content. A pronounced increase in Ca/Na ratios under a dense canopy cover have been recorded.
- (4) Changes in chemical characteristics of soil in the rooting zone are discernible after prolonged growth of trees and depend upon the amount and composition of litter fall.

**INTRODUCTION**

Soil degradation through salinization and alkalinization has become a major factor limiting crop production in many countries of the world. Amelioration and utilization of salt-affected soils have been the focus of research attention of agricultural scientists for over half a century. In alkali soils, chemical amendments such as gypsum, pyrites, sulphuric acid and sulphur have been used with varying degrees of success. It is being increasingly recognized that the use of chemical amendments is costly in labour and energy. More emphasis is, therefore, being placed on selecting and developing varieties of plants which are tolerant to soil alkalinity.

In India soil alkalinity is a major problem affecting nearly 7 million hectares of land (Abrol and Bhumbra 1971). The problem is more acute in the Gangetic plains of northern India. Investigations carried out at various research institutions in the country have shown the possible utilization of alkali soils for afforestation (Yadav 1980). This paper presents a review of the work on amelioration of alkali soils which have been carried out at the National Botanical Research Institute, Lucknow, for over 30 years since the establishment of a research station at Banthra in 1956.

+ Deceased, May 1986

### CHARACTERISTICS OF THE SOIL

Data on physical and chemical characteristics of the soil at Banthra Research Station (Tables 1 & 2) show that the soil is silty loam to silty clay loam in texture. There is a hard impermeable pan of calcium carbonate at 50-75 cm depth (the 'kankar' zone). The carbonates are mainly in the form of gravel. Concretions other than the granules of lime are also noticed. Within the profile, pH goes on increasing and is maximum (10.2) in the vicinity of the 'kankar' zone. Organic carbon is uniformly low. Available phosphorus and potash increase with depth and are maximum in the middle zone. Exchangeable calcium is high on the surface and decreases with the depth of the profile. In contrast, exchangeable magnesium and sodium are low at the surface but increase with the depth. The cation exchange capacity of the surface soil is 12 me/100 g.

TABLE 1: Physical properties of soil profile at Banthra 1964.

Depth cm	Mechanical composition				W.H.C. %
	Gravel	Sand	Silt %	Clay	
0-20	7.4	43.4	30.0	26.0	Sl 34.02
20-56	12.6	33.4	30.0	36.6	Scl 38.85
56-78	7.2	29.4	28.0	42.6	Scl 37.27
78-110	8.9	23.4	36.0	40.6	Scl 38.42
110-152	14.7	39.7	26.0	Scl	32.90

TABLE 2: Chemical characteristics of soil profile at Banthra 1964

Depth cm	pH	TSS*	CaCO <sub>3</sub>	OC	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Ca	Mg	Na	CEC <sup>+</sup>
		(	%	)	(kg/ha)		(	me/100 g)		
0-20	9.6	0.14	0.82	0.19	14	312	16.2	1.0	9.26	12.6
20-56	10.2	0.22	1.03	0.08	29	280	11.8	4.2	15.26	12.3
57-78	10.2	0.20	0.57	0.10	30	640	5.6	12.4	15.52	14.1
78-110	9.6	0.11	0.50	0.11	32	600	5.8	7.2	11.16	15.1
110-152	9.1	0.08	0.28	0.11	11	380	6.4	9.2	4.36	14.2

\* TSS = Total Soluble Solids/Salts

+ CEC = Cation Exchange Capacity

### QUALITY OF IRRIGATION WATER

Good quality irrigation water is essential for amelioration of alkali soils. At Banthra water from cavity tubewells sunk 30-35 metres deep had the following chemical composition (Table 3).

TABLE 3: Quality of irrigation water at Banthra.

Characteristics	Range
pH	7.4-7.9
EC mmhos/cm	610-1220
C1 me/l	0.30-0.80
SAR*	1.30-1.88
RSC*	0.27-4.89
SSP*	33.33-40.36

\* SAR = Sodium Absorption Ratio  
 RSC = Residual Sodium Carbonate  
 SSP = Soluble Sodium Percentage

According to Bhumbla and Abrol (1972), waters having RSC of 5 me/l with EC less than 400 mmhos/cm are safe for irrigation.

### BIOLOGICAL AMELIORATION

A distinctive feature of the experiment at Banthra was improvement of the soil through biological means using organic materials that were available in the vicinity of the farm. No chemical amendments were used.

### AMELIORATION BY TREES

In a selected area of 2.5 hectares where amelioration by arboreal plant species was attempted, small bunds having a height of 25 cm were made to impound and regulate rain and irrigation water. On the bunds, trees such as Acacia nilotica, Albizia lebbek, Dalbergia sissoo and Derris indica, were grown by direct seed sowing. Between the bunds, tolerant shrubs such as Clerodendrum indicum, Ipomoea fistulosa, Jatropha gossypifolia, Sesbania aegyptiaca, Sesbania grandiflora, Leucaena glauca and Vitex negundo were grown.

For a number of species, beaking of hard pan was considered necessary. Pits to a depth of 1m were dug and refilled with soil taken from ditches, thin cinders (burnt coal from mills or railways), river sand and available organic matter.

Success in ameliorative afforestation of sodic, or for that matter salt-affected soils, depends on judicious selection of plant species. Alkali soils are characterized by patchiness though they have the common property of preponderance of sodium. In places, where the 'kankar' layer was exposed, Prosopis juliflora, Acacia nilotica, Acacia farnesiana, and Parkinsonia aculeata were found to grow successfully. In waterlogged areas Salix tetrasperma, Typha elephantina, Pandanus tectorius and Acorus calamus could be raised. Amongst shrubs, species such as Thevetia peruviana, Nerium indicum, Clerodendron inerme, Lawsonia inermis and Tecoma stans could be grown successfully.

### TERRESTRIAL ECOSYSTEM

Today this 2.5- hectare piece of land, bereft of vegetation 30 years ago, is a thick forest supporting habitation to animals such as langoors, rabbits, birds and reptiles. it is an ecosystem that has been developed directly from halosere (barren alkali soil) through some induced successional stages by human interference.

The forest community is dominated by the following tree species: Acacia nilotica, Albizia procera, Dalbergia sissoo, Ficus benghalensis, Syzygium cumini and Terminalia arjuna. The middle storey consists of shrub species such as Cassia occidentalis, Ipomoea fistulosa and Lantana camara. The ground storey supports several grass species.

TABLE 4: Soil characteristics under canopy cover of trees in man-made forest at Banthra 1982.

Tree species	pH	EC micro mhos/cm	ESP* %	OC %
Open ground	10.2	792	73.4	0.39
<u>Acacia nilotica</u>	8.3	254	52.6	0.75
<u>Albizia procera</u>	7.9	233	43.1	0.90
<u>Bauhinia variegata</u>	8.4	378	47.3	0.90
<u>Dalbergia sissoo</u>	8.8	205	50.3	0.81
<u>Ficus bengalensis</u>	8.7	334	47.9	0.60
<u>Syzygium cumini</u>	8.3	182	45.0	0.84
<u>Terminalia arjuna</u>	8.5	353	52.7	0.90
<u>F. bengalensis + S. cumini</u>	8.0	276	44.7	0.90
<u>T. arjuna + A. nilotica</u>	8.1	242	43.1	0.81
<u>A. nilotica + D. sissoo,</u>	7.2	633	42.3	1.17
<u>S. cumini, F. bengalensis</u>				
<u>Phyllanthus emblica</u>				

\*ESP = Exchangeable Sodium Percentage

The ameliorative effect of tree canopy cover on soil is evident from the data presented in Table 4. Among the individual tree species, the maximum reduction in soil pH was recorded under Albizia procera followed by Acacia nilotica and Syzygium cumini. The mixed canopy of five species was most effective in reducing soil pH. Electrical conductivity was also reduced under mixed canopy. However, on sodic soils, this parameter is of little significance. Maximum reduction in ESP was brought about under the canopy of Terminalia arjuna and Syzygium cumini. Organic carbon content in the 0-30 cm layer increased from 0.39 to 0.90 per cent. As the changes were more pronounced in 0-30 cm layer, the data on various characteristics of soil at this depth are

presented (Verma et al. 1982). Maximum numbers of annual species grew under the canopy of Albizia procera followed by that of Acacia nilotica. In the open area with no tree cover, a few annual species were found to grow. Variation in the ameliorative effect of different tree species may be attributed to differences in the amount of litter fall and leaf composition.

A concurrent study of soil characteristics in the rooting zone of 10-year old trees of Acacia nilotica var cupressiformis, Bauhinia diphylla, Callistemon phoeniceus, Derris indica and Terminalia arjuna showed that pH in the 0-15 cm layer ranged from 9.1 to 9.6 and at 15-45 cm depth from 9.6 to 9.8. Variations in soil exchangeable cations were not reflected in leaf composition (Garg and Khandjun, 1979). It has been shown by Yadav and Singh (1970) that Acacia nilotica was able to grow well on moderately calcareous soils with pH 9.0. Derris indica and Terminalia arjuna were found to grow satisfactorily on soils with a pH up to 9.8 and soluble salts up to 0.45 per cent. The species included in our study seem to tolerate high levels of soil sodicity.

In another study of interaction of four fruit tree species, Emblica officinalis, Psidium guajava, Mangifera indica and Ziziphus jujuba, with the soil on which they had been growing for over 15 years, it was observed that soil pH was decreased in the 0-15 cm layer. Psidium guajava recorded the lowest pH 8.6 at 15-45 cm and 45-75 cm depths. Organic carbon concentration was increased under the canopy of all the four species with Ziziphus jujuba showing the maximum accumulation of 0.40 per cent. Exchangeable sodium decreased, but potassium increased in the 0-15 cm layer under all the species. Ziziphus jujuba showed the maximum reduction in exchangeable sodium. The increase in calcium content was noticed in the 15-45 cm layer.

These studies show that tree species exert a varied influence on chemical characteristics of the soil under their canopies.

Based on empirical observations on the performance of various tree species on sodic soils of Banthra for over 25 years, a statistically designed experiment to evaluate biomass productivity of twelve selected tree species was laid out in 1981. The chemical characteristics of the soil at various depths of the profile excavated at the beginning of the experiment, and of the rooting zone of Prosopis juliflora three years after their establishment, are given in Table 5. The data show that pH in 0-3 cm layer is reduced, organic carbon and Ca+Mg content are increased. A similar trend was discernible under Terminalia arjuna and Acacia nilotica. Ameliorative effects of Prosopis juliflora on the soil have been reported by Yadav and Singh (1970) who observed a decrease in pH soluble salts in the upper 15 cm layer. Recently Rao and Ghai (1985) have reported a reduction in pH and an improvement in organic carbon of soil under tree cover.

TABLE 5: Chemical properties of soil in the rooting zone of Prosopis juliflora three years after planting.

Profile depth cm	pH	EC mmhos/ cm	OC %	Na (	K me/100g	Ca+Mg )
Original soil (1981)						
0-15	8.75	.430	0.30	5.67	0.60	16.75
15-45	9.20	.495	0.18	8.64	0.52	14.49
45-75	9.95	1.500	0.51	12.28	0.76	14.37
Three years after (1984)						
0-3	8.21	0.47	0.57	1.30	0.62	37.67
3-15	8.98	0.50	0.29	2.64	0.55	36.83
15-30	8.93	0.54	0.18	5.14	0.53	28.17
30-45	8.94	0.44	0.14	5.25	0.50	29.34

In another experiment with four species of shrubs planted at densities of 25000, 50000 and 75000 plants/ha, an appreciable fall in pH and increase in organic carbon content of soil was recorded as a consequence of plant growth. The most significant change in soil was increase in Ca/Na ratio under all the four species, in particular Sesbania aegyptiaca at density of 75000 plants/ha (see Table 6). This could be due to increased solubility of the calcium existing in immobile state in the alkali soil.

TABLE 6: Chemical characteristics of soil under canopy cover of Sesbania aegyptiaca in high density plantation.

Planting density plants/ ha	Soil depth cm	pH	EC mmhos/ cm	OC %	Mg (	Ca me/litre	Na )	Ca/Na ratio
25000	0-15	9.46	0.74	0.34	61.68	239.52	133.48	1.79
	15-30	9.70	0.85	0.26	37.00	149.70	141.74	1.05
50000	0-15	9.79	0.81	0.22	69.90	157.18	94.35	1.66
	15-30	9.80	0.92	0.12	65.79	97.30	142.17	0.56
75000	0-15	9.31	0.55	0.38	26.31	146.70	54.35	2.70
	15-30	9.65	0.82	0.12	23.02	84.33	130.43	0.64

## **CONCLUSION**

This review brings out the possibility of utilizing alkali soils without prior reclamation by planting tree species which are tolerant of soil alkalinity. Success in afforestation of alkali soils will depend upon judicious selection of plant species and proper soil management practices keeping in view the heterogeneous microrelief of the soil. Species with rapid juvenile growth and aggressive root systems that are able to grow successfully on alkali soils have been identified.

The ameliorative effects of tree cover on the soil are reflected in reduced pH and increased organic carbon content, and differ with the tree species depending upon the amount of litter fall and its chemical composition. In densely planted stands, improvement in soil composition is rapid and more pronounced in the surface layer.

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#### 4. RECLAMATION OF MINE WASTELAND BY TREES

M.N. JHA

Forest Research Institute, New Forest, Dehra Dun, India

##### SUMMARY

Reclamation of mine wasteland by tree plantation is essential for recovery of land, from both an environmental and an economic perspective. In India, a country rich in mineral resources, such reclamation of mine wasteland will be necessary due to a substantial increase in mineral exploration. The problem of reclamation would be most acute in Bihar and Madhya Pradesh which are rich in minerals.

The successful reclamation of such lands through plantation of trees has been achieved in Amarkantak (Madhya Pradesh), and this is described.

##### INTRODUCTION

In the process of mining, the natural and organised sequence of the soil and other biological forms, is destroyed. The exploitation of the land for minerals leaves behind dumped mine wastes or spoils. This is the area which must be reclaimed through biological means. In this presentation, reclamation of mine wasteland by trees has been discussed through a case study.

##### MINERAL EXPLOITATION IN INDIA

India is well endowed with natural resources. The exploitation of these resources is increasing. The production figures of some recent years is an illustration of this fact. (Table 1).

TABLE 1: Total Value of Mineral Production in Recent Years

Year	Value (in million rupees)
1979	17,420
1981	34,320
1982	48,750

It is important to note that this total production of Rs.48,750 million is mainly composed of mineral fuels such as coal, lignite, petroleum and natural gas. The value and proportion (of total production) of different minerals is described in Table 2.

TABLE 2: Production and % of Total Production of different Minerals

Mineral	Production (in million rupees) (1982)	% of Total Production
Coal, Lignite, Petroleum and Natural Gas	44,220	87.51*
Metallic Minerals	2,780	5.5
Non-metallic Minerals	1,747	3.46
Other Minerals	1,786	3.53

\*solid fuel-41.23%, liquid fuel-44.19%, gas-2.09%

Such figures, however, do not illustrate the extent to which exploration results in regions of mine waste. A knowledge concerning the nature of mineral deposits and what mining techniques are to be employed, would provide a good starting point for determining the dimensions of the problem of resulting mine wastes. According to one estimate, the mine waste dumped annually the world over is about 3,000 billion tonnes. The area of land concurrently disturbed by mining approximates 386,000 ha per year and in the last quarter of the century, areas of mine waste amounted to 24 million ha. This is about 0.2% of the earth's surface. The working group on the environment (1981) has listed 20 minerals, whose mining could cause serious problems which would require immediate attention.

### FEATURES OF MINE WASTES

These lands can vary from steep slopes to mild undulations (if machines have been used for levelling). They are generally arid and barren with surface material ranging from boulders and stones or loose sand to sticky clay with impeded drainage. A major feature of mine wastes is that they are formed from disorganised material. Thus, the rooting medium can vary greatly. There may be waterlogging, toxic elements and gases which the roots may have to withstand. Planting of these areas with suitable tolerant species is the most suitable way to reclaim the land. Plants have a unique capacity to improve the landscape and at the same time offer economic benefits. However, if they are not revegetated, neglected mine wastes not only ruin the immediate environment but also eventually erode. This results in pollution and silting of water supplies thereby degrading the economic and aesthetic value of the area.

Rehabilitation of mine wastes is a slow and expensive process. In many situations, therefore, it is suggested that reclamation work proceed concurrently with the mining.

### RECLAMATION OF MINE WASTE - A CASE STUDY

The effectiveness of reclamation through the use of trees has been shown recently in Amarkantak in the state of Madhya Pradesh (M.P.). This case study is briefly discussed.

### Location

Bauxite ores are an important source of aluminium in India. India's total reserve of bauxite is 3,489 million tonnes (1980). M.P. has deposits in as many as five districts. The state has about 100 million tonnes of bauxite reserve. The bauxite is mined in Amarkantak which falls in sal zone and in a catchment area of important rivers such as the Sone, Mahanadi and Ganga. The work was carried out in Ratti Dadar, Nanhu Dadar and Khurkhuri Dadar. BALCO, a public company, is mining the metal in this area. Natural vegetation in the area consists of Shorea robusta, Terminalia tomentosa, Pterocarpus marsupium and Anogoissus latifolia.

### Mineral

Bauxite is associated with laterites in India. A mixture of ferric hydroxide, aluminium hydroxide and silica in various proportions is termed true laterite. If it contains greater than 50% Al, it is termed bauxite. It is found in the form of colloidal hydrogels, with variable amounts of combined water. Impurities such as silica (as clay mineral or quartz), iron, titanium, lime, magnesium and manganese may also be present. It is a dirty white, light grey, cream pink or reddish brown rock, which may be amorphous, compact, earthy, granular or porous.

### Mining

BALCO has mined about 200 ha through the use of heavy machinery for felling trees, shovelling, digging and scraping etc. Top soil is removed along with overburden of laterite and bauxite and dumped on the escarpment. The company only fills up the pits which are 8 to 10m deep. The surface is full of boulders and bauxite rejects.

### Plantation of Forest Species

After levelling the site by bulldozing, pits of 45cm<sup>3</sup> were dug up at 2m x 2m spacing and used for planting different species. Soil from nearby sal forest was imported to fill up the pits, along with additional compost. Some properties of mine wastes are shown in Table 4.

TABLE 4: Some Properties of the Mine Waste

Boulder Area Depth cm	pH	Organic Matter %	*N kg ha <sup>-1</sup>	*P kg ha <sup>-1</sup>	*K kg ha <sup>-1</sup>
0-25	5.50	1.54	380	6.3	840
25-90	6.75	0.82	313	2.7	280
90-180	6.40	0.38	168	0.9	224
180-300	6.30	0.26	90	0.9	112

\* average content

The rooting medium for seedlings was essentially the good soil which was initially present in the area. However, the roots beyond the pit faced deficient soil phosphorous although the material was reasonably supplied with nitrogen and potassium. Surface pH was acidic and solubilized Al and associated ions were present in the medium. Some nitrogen could have been left over in the mine waste through unexploded ammonium nitrate (explosive was used in these mines).

### Performance of Tree Species

Ten tree species were planted in 1979 in six blocks. The height of the plants and the survival of the species were noted in 1980 to 1985 as per Table 5.

TABLE 5: Performance of different species planted on the mine waste

Species	Year							
	1980		1981		1982		1983	
	ht (cm)	Survival (%)	ht (cm)	Survival (%)	ht (cm)	Survival (%)	ht (cm)	Survival (%)
<u>Moringa Spp</u>				FAILED				
<u>Acacia aur- culiformis</u>	101	90	211	87	343	87	412	87
<u>Eucalyptus camaldulensis</u>	352	93	770	93	1365	93	1678	93
<u>Melaleuca leucadendron</u>				FAILED				
<u>Pinus caribae</u>	135	91	234	91	298	91	335	91
<u>Pinus rox- burghii</u>	56	97	111	96	177	95	209	95
<u>Grevillea robusta</u>	163	98	250	97	338	96	388	96
<u>Shorea robusta</u>	48	92	77	90	110	90	122	90
<u>Grevillea pteridifolia</u>	220	96	501	94	658	94	728	94
<u>Pongamia pinn- ata</u>	43	88	94	83	156	83	180	83

The Melaleuca species, which is an exotic, could not survive due to its moisture requirements and biotic interference. The other plant species continue to survive even after 7 years. Two species, Shorea robusta (Sal) and Pongamia pinnata (Karanj), are indigenous varieties, while the remaining species are being tried in the Australian bauxite mines with great success. Of the various species tried, Grevillea pteridifolia, has been contributing maximum litter to the soil surface followed by Eucalyptus and Pinus caribaea.

### Suggestions

In order to ensure that reclamation is successful, various factors must be taken into consideration. Before afforestation of mine wastes, the lands must be stabilized by erosion control measures which include grading of steep slopes, partial resurfacing with fertile soil and mulching and spreading of slash. The technique of amelioration varies widely depending on the composition of the

regolith or the mine waste, and afforestation must be preceded by careful physical and chemical analysis of the debris. Special attention should be given to the texture of the exposed substratum, its permeability to air and water, aeration at field capacity, content of carbonates, supply of available mineral nutrient elements, electrical conductance and presence of toxic substances. Because of the deficiency of organic matter in the soil, wide use of tree and shrub legumes should be made. The depressions where water collects may also be utilized by planting suitable tree species.

Wastes deficient in nutrients may require the application of fertilizers for the successful establishment of plants species. There may even be a necessity to chemically correct extreme toxicity. Plants may also require protection from disease, pests, biotic interference and frosts.

Clearly, the scope is wide for amelioration of mine waste by trees.

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## CHAPTER IV

### ASSOCIATIONS OF MICROORGANISMS WITH TREES - AN AID TO SOIL AMELIORATION

In arable systems, nitrogen fixation through Rhizobium/legume symbioses currently provides a higher nitrogen input to soils (as plant residues) on a global basis than nitrogen fertilizer applications. Management of legumes and of legume residues is therefore a key factor in sustained crop production.

Many tropical soils are inherently deficient in nitrogen, a primary soil nutrient for plant growth. Where legume crops are not part of the agricultural system, legume trees could be valuable in adding nitrogen to the agroecosystem. Not all legumes fix nitrogen. The potential nitrogen - fixing abilities of legume trees in the three legume sub-families, Caesalpinioideae, Mimosoideae and Papilionoideae are discussed by J. I. Sprent in Section I of this chapter. In Section 2, Sesbania sesban, a legume tree, is evaluated as a soil conditioner in relation to its broad tolerance of extreme physiological conditions as well as its nitrogen fixing abilities.

Legumes are not the only group of woody species capable of fixing nitrogen. Casuarina, a non-leguminous tree is nodulated by the nitrogen-fixing filamentous soil bacterium, Frankia. Casuarina also grows well under extreme soil conditions such as high salinity, and therefore has considerable potential in soil amelioration. The biological and environmental factors affecting the symbiosis between Casuarina and Frankia are discussed in Section 3 of this Chapter. This symbiosis is further investigated in section 4 by P. A. Rosbrook. In this section, the sources of Frankia capable of nodulating and effectively fixing nitrogen in symbiotic associations with various Casuarina species are screened.

Another way in which microorganisms in association with trees can improve soil productivity is through the mutualistic association of fungi with roots, known as mycorrhizae. Mycorrhizae increase the trees' absorptive capacity and uptake of nutrients and water from the soil and promote tolerance to drought, salinity and heavy metals. Mycorrhizae also bind soil particles, forming soil aggregates, and can therefore be of primary importance in forming and maintaining soil structure.

Because of their ability to take up nutrients which are otherwise unavailable to the plant, and to directly take up nitrogen and phosphorous from litter, mycorrhizae play an important part in conversion of nutrients and in nutrient cycling. The role of mycorrhizae in soil amelioration is considered in section 5 and mycorrhizae research in India is reviewed.

1. NITROGEN FIXING LEGUME TREES:  
PROBLEMS AND MISCONCEPTIONS

J. I. SPRENT

Department of Biological Sciences,  
University of Dundee, DD1 4HN, Scotland

SUMMARY

A number of important legume trees, particularly in the sub-family Caesalpinioideae, cannot nodulate. Others, which have the potential to nodulate, may not do so in extreme environments. The occurrence of nodulation is discussed especially in relation to the type of nodule produced and the problems which need to be solved before their nitrogen fixing potential can be optimised.

INTRODUCTION

The family Leguminosae probably evolved in the tropics, early in the evolution of flowering plants (Pohill et al, 1981). From there it spread into temperate and arctic regions, becoming progressively more herbaceous in habit. These temperate, herbaceous species, together with some sub-tropical crop relatives, almost all of which are from the sub-family Papilionoideae, have dominated research into legume physiology. It is becoming increasingly clear that tree legumes do not obey many of the rules of their herbaceous descendants. This is particularly true of their potential to fix nitrogen. The purpose of this paper is to put the problems and the potentials for nitrogen fixing trees into perspective.

TAXONOMIC FRAMEWORK, CAESALPINIROID SPECIES

It has been known for many years (see data summarised by Allen et al, 1981) that Caesalpinoid legumes nodulate less frequently than their Mimosoid and Papilionoid counterparts. This still holds, although a number of new reports of nodulated species have been made recently (Faria et al, 1984 and in preparation). In many cases the literature is ambiguous. *Bauhinia* for example is generally considered to be a non-nodulating genus (Allen et al, 1981, list 27 species reported to lack nodules and Faria et al, 1984 have added a further 4) and yet Quinones (cited by Domingo, 1983) claims to have isolated rhizobia from nodules of *B.purpurea* (one of the species for which Allen et al, 1981 cite three negative reports of nodulation). *Parkinsonia aculeata* is listed as nodulated by Halliday et al (1981), but the references given to support this all report absence of nodules, so one suspects that a '+' was included in the table instead of a '-'. Extensive searches for nodules in Brazil (Faria pers. comm.) and Central America (Roskowski, pers. comm.) have yielded negative results. However, there are unconfirmed reports that this species nodulates in the Sudan. Since it is being recommended for introduction into arid areas (Hughes et al, 1984) it is desirable that this conflict is resolved. We have grown *P.aculeata* with a rhizobial inoculant from NifTAL (the centre for rhizobial inoculants in Hawaii) and with many strains of rhizobia from Brazil and none has yielded functional nodules. However, outgrowths from the junctions between main and lateral roots, superficially like nodules of *Arachis* (peanut, groundnut) are often seen.

One possibility is, therefore, that these pseudonodules, which result from division of a phellogen, have been mistaken for nodules. Although it has serious limitations as a quantitative assay, an acetylene reduction test (as used by Faria et al, 1984) should always be performed on any structure suspected of being a nodule. An alternative is to fix nodules and examine them for the presence of infected cells, consulting a suitable authority in the case of unusual nodule structures.

A further possibility in the case of Parkinsonia is that it nodulates in some countries but not in others. Geographical restrictions on nodulation have been known amongst actinorhizal nodulated plants for a number of years (Bond, 1976) and appear to hold also for some legume genera. Pterocarpus spp. (Papilionoideae) for example, apparently nodulate in Africa, Asia and Venezuela (Allen et al, 1981) but not in Brazil (Faria et al, 1984). Another possible source of confusion is misidentification of the legume - some are very difficult to identify, especially when not flowering. The taxonomy of many of these groups is under revision. The genus Cassia for example has recently been divided into three, Cassia, Senna and Chamaechrista (Irwin et al, 1982). All the nodulated cassias have, for other reasons, been placed in Chamaechrista.

Many trees of established and potential commercial significance are apparently non-nodulated members of the Caesalpinioideae. These include Baikaea plurijuga which yields valuable timber (Allen et al, 1981). Of the five legume trees listed by Hans (1985) as important fruit species in Zambia, three, (Dialium englerianum, Guibortia colesperum and Tamarindus indica) are Caesalpinioid and one (Cordyla africana), classified as Caesalpinioid by Hans (1985) has now been transferred, with other members of the tribe Swartzieae to the Papilionoideae (Cowan, 1981). In none of these could Corby (1974) find nodules in the neighbouring state of Zimbabwe. There are no confirmed reports of nodules on Cassia siamea, a tree widely grown in Africa and elsewhere. The fact that many important Caesalpinioid legumes do not nodulate does not, of course, detract from their value as crops in comparison with non-legume species. Bauhinia for example yields high quality forage (Robinson, this volume). Further, their success in some nutrient poor soils may relate to a general efficiency in nutrient acquisition and in this way they should be evaluated against non-legumes (see also Okigbo, 1984). Such trees may improve nutrient cycling and nitrogen levels in upper soil layers, but will not increase total soil N.

Amongst nodulated Caesalpinioid trees, work has concentrated so far on describing nodule morphology and on isolating rhizobia (Corby, 1974; Allen et al, 1981). Infection processes, nodule structure and nitrogen fixing activity have been largely ignored, mainly because of lack of facilities in areas where these plants grow. Faria and Sprent (in preparation) have found considerable similarity in internal structure within Caesalpinioid nodules, but major differences from nearly all other known nodule structures. Some nodules are themselves black and woody, due to extensive sclereid production and thick walled xylem elements. Work on estimating the nitrogen fixing potential of these nodules is commencing, but field studies are urgently needed in all those countries where the plants grow naturally. Only then can improvement programmes be seriously undertaken.

#### MIMOSOID TREES

Most of these have the potential to nodulate, although there may be geographical variation in the genus Parkia. Nodules have been found in Asia and

Hawaii (see references in Allen et al, 1981), but Norris (1969), confirmed by Faria et al, 1984 could find none in Brazil.

Mimosoid trees are very important in arid and semi-arid regions throughout the world and some genera, such as Prosopis have great drought and salinity tolerance. However, such evidence as is available (discussed in Sprent, 1985, 1986) suggests that even though they can nodulate, they may not do so under extreme environmental conditions. Even when nodulated, active nitrogen fixation only appears to occur when water is available. However, they have many important attributes, including being multipurpose plants and having deep roots. Investment of plant resources in root systems in generally nutrient poor soils is of more potential value than investment in nodules which only alleviate N deficiency (Sprent, 1985). The key to the success of Mimosoid trees in dry and/or saline environments is more likely to result from deep roots than nitrogen fixation.

### PAPILIONOID TREES

Most of these are nodulated although there are some exceptions (particularly in some of the more primitive tribes which contain trees, Faria et al, 1984). The type of nodule varies considerably. Common amongst the tribe Dalbergieae, which includes the important timber, incense and fodder genus Dalbergia, are small nodules of limited growth, located in the axils of lateral roots (Faria et al, 1984). They appear to form very freely, not only on young roots, but also on old roots among earlier formed, senescent nodules. This property might give them a versatility not possessed by species which nodulate only on young roots. Erythrina, normally included in the tribe Phaseoleae, has nodules similar to those of Dalbergia. An interesting special case of this type of nodule is found on the stems of the genera Sesbania (Tsien et al, 1983) and Aeschynomene (Vaughn et al 1985). These too are associated with root initials. They form most readily when soils are flooded, reducing the extent of root nodulation. In the case of Sesbania rostrata different rhizobia and modes of infection may be used for stem and root nodules on the same plant (Olsson et al, 1985).

Nodules on most of the other Papilionoid trees (e.g. Sophora, Robinia, Wisteria) that have been examined, show indeterminate growth, as do most Mimosoid nodules: many are branched and perennial. Often, like Mimosoid nodules, the older parts become corky on the surface as compared with looser aerating tissue on the surface of the young, active nitrogen fixing regions. Indeterminate growth, as in advanced herbaceous species such as the clovers, enable plants to recover from some forms of environmental stress, such as drought, by growing new nitrogen fixing tissue (Sprent, 1976, 1985).

### TREE LEGUME RHIZOBIA

Like their nodules, tree legume rhizobia do not conform to the familiar patterns found in temperate crop species. Growth rate (fast, intermediate, slow or very slow, compared with fast or slow) varies both within and between host genera (Allen et al, 1981; Trinick, 1982; Barnet et al, 1985). Many are rather promiscuous, nodulating a variety of species. If this promiscuity is similar to that on herbaceous genera, then there is likely to be a big range in nitrogen fixing efficiency. This has been shown for example in introducing soybean (Glycine max) to Nigeria, where many poorly effective or ineffective nodules form with indigenous rhizobia which normally nodulate cowpea (Vigna

unguiculata) (Devine, 1984). These problems need to be studied and taken into account in any programme to enhance nitrogen fixation by nodulated legume trees.

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## 2. NITROGEN FIXATION AND BIOMASS PRODUCTION

### BY *SESBANIA SESBAN* IN ALKALI SOILS

D.L.N. RAO, H.S. GILL AND I.P. ABROL

Central Soil Salinity Research Institute, Karnal-132001, India.

#### SUMMARY

(1) *Sesbania sesban* was evaluated in pot and laboratory studies for nodulation, N fixation in an alkali soil and tolerance to salinity and alkali at germination. Field experiments on green-manure potential and biomass production were carried out at an alkali site.

(2) On an average, *S. sesban* had 36 nodules plant<sup>-1</sup>, nodule biomass (dry) of 92 mg plant<sup>-1</sup>, 2.3 g dry wt. plant<sup>-1</sup> and N content of 3.5% at the 30 day growth stage. Native rhizobia produced excellent nodulation and actively competed with inoculated strains.

(3) *S. sesban* could tolerate EC 11.0 (0.7% salts) and pH 10.0 at germination. It produced a biomass (oven-dry) of 5.2 and 12.7 t ha<sup>-1</sup> at 100 and 200 days growth respectively. In long term experiments it produced air-dry biomass of 87 t ha<sup>-1</sup> in 3 years. At 100 days growth the green-manuring potential was (kg/ha) 64 N, 5 P and 52 K. At 200 days it was (kg/ha) 59 N, 4 P and 38 K.

#### INTRODUCTION

*Sesbania sesban* (Linn.) Merrill (Syn. *S. aegyptiaca*) is a soft-wooded, quick growing, short-lived tree cultivated throughout the plains of India. It branches copiously, growing to a height of 4.5 - 6m. It forms root nodules by symbiotic association with *Rhizobium* sp. capable of fixing atmospheric nitrogen. It is often grown as a perennial green manure crop. The plant stands lopping well and produces regrowths quickly. It tolerates a wide range of soil conditions, including acidity, periodic flooding and water-logging (Anonymous, 1983). It can endure 0.4-10% salt concentration at the seedling stage and 0.9-1.4% near maturity (Jen et al., 1965). The plant has been reported to grow up to 5m in 12 months and the yield recorded in India was up to 75 t ha<sup>-1</sup> (10% moisture) in 1 year (Anonymous, 1983).

Work on the growth and nitrogen fixation of *S. sesban* in alkali soils is lacking. An initial report (Kumar, 1983) showed that *S. aegyptiaca* (syn. *S. sesban*) could tolerate pH 9.9 at germination and pH 9.5 at later growth stages in pot experiments. In the present studies, *S. sesban* was screened for its tolerance to salinity and alkali at germination in laboratory studies and for its use for foliage and fuel wood production in field experiments on an alkali site. A comparative evaluation of nodulation and nitrogen fixation by eight strains of *S. sesban* is also reported.

## MATERIAL AND METHODS

### Germplasm

Eight varieties of *S. sesban* were collected from different sources in India and from the United States Department of Agriculture. Before germination, the seeds needed to be soaked in water overnight or scarified in concentrated sulfuric acid for different periods (Table 1).

### Nodulation and nitrogen fixation by *S. sesban*s

Surface soil of the CSSRI Farm (Sandy loam, pH 9.2, ESP 32, EC 0.3 mmhos cm<sup>-1</sup>, organic C 0.4%, total N 0.04%, available N 90.0 kg ha<sup>-1</sup>) was used for a pot experiment to assess nodulation and N fixation by *S. sesban*. Before sowing, an effective strain of the *Rhizobium* sp. for *S. sesban* was inoculated on the seeds using standard techniques (Vincent, 1970). Uninoculated seeds served as a control. Plants were uprooted at 30 days to score for nodulation, biomass, and nitrogen accumulation in the shoots. *Rhizobium* sp. isolated from the nodules was used for antibiotic marker pattern studies and the native and the inoculated *Rhizobium* sp. were compared.

### Salinity and alkalinity tolerance at germination

For studying the effect of salinity, the seeds were allowed to germinate on filter papers kept continuously soaked in solutions of four salinity levels (EC 5, 11, 15 and 18 mmhos cm<sup>-1</sup>). The salinized solutions were prepared with NaCl, Na<sub>2</sub>SO<sub>4</sub> and CaCl<sub>2</sub> keeping a Na:Ca ratio of 4:1 and Cl : SO<sub>4</sub> ratio of 4:1. Distilled water (EC 0.02 mmhos cm<sup>-1</sup>) was included as a control. For checking the effect of alkalinity, Na<sub>2</sub>CO<sub>3</sub> solution of pH 8.0, 9.0, 10.0 and 11.0 were used.

### Green manuring potential and biomass accumulation (Short-term study)

To evaluate the potential of *S. sesban* CSSRI to supply nutrients through green manure and to study biomass production in short periods of growth in the summer and in the rainy season, a field experiment was set up in the summer of 1985. The soil was sandy loam, pH 8.5, ESP 15, EC 0.2 mmhos cm<sup>-1</sup>, organic C 0.5%, total N 0.06% and available N 55kg ha<sup>-1</sup>. *S. sesban* was sown at four seed rates ( 5, 10, 15 and 20 kg/ha) by broadcasting the seeds in thin standing water in 6 x 6m plots. The treatments were replicated four times in a randomized block design. In one replication plants were harvested at 100 days and N, P, K and biomass accumulation through leaves and stem estimated. At 200 days the plants from another replication were harvested and nutrient and biomass accumulation in leaves and stem were evaluated. In calculations of green-manuring potential only the leaves and the tender 'top' portions of the stems were considered.

The experiment started on 5 May 1985 and terminated on 20 November, 1985. The mean maximum and minimum temperatures during the first 100 days growth ranged from 32.7 to 40.7°C and 23.2 to 27.0°C respectively. The mean maximum ranged from 27.0 to 32.2°C and the mean minimum from 10.7 to 23.0°C during the last 100 days of growth. The crop was irrigated as and when there were symptoms of stress.

### Biomass accumulation (Long term study)

Seeds of *S. sesban* CSSRI were sown in August 1982 by dibbling at a distance of 1m, maintaining 3m distance between the rows over an area of one hectare. Biomass accumulation in 3 years was recorded.

## RESULTS AND DISCUSSION

### Nodulation and nitrogen fixation by *S. sesban*s

There was a range of variation among the strains in the nodule no., nodule biomass, plant dry weight and shoot N content at 30 days (Table 1).

TABLE 1: Nodulation and N fixation by *S. sesban*s at 30 days growth stage in an alkali soil (pH 9.2, ESP 32).

Acq. No.	Source and origin	Germination treatment	Nodulation No. plant	Dry wt. (mg) of nodules	Biomass g plant <sup>-1</sup>	Shoot %N
05	MPKV, India	W	17	53	2.7	3.7
06	GAU, India	W	18	110	1.6	3.2
07	CSSRI, India	A <sub>20</sub>	17	68	1.1	2.7
09	IGFRI, India	A <sub>15</sub>	45	125	0.7	3.4
31	USDA 215608, India.	A <sub>45</sub>	71	116	3.1	4.0
32	USDA 228236, India.	W	63	124	3.0	2.4
33	USDA 233551 Okinawa.	A <sub>15</sub>	37	75	2.6	4.4
34	USDA 279601, China	A <sub>5</sub>	21	74	3.9	4.0
Mean			36	92	2.3	3.5
S.D.			20	28	1.0	0.6

a

W = germinated by soaking in water; A<sub>5</sub>, A<sub>15</sub>, A<sub>20</sub>, A<sub>45</sub> = germinated by soaking in concentrated sulphuric acid for 5, 15, 20, 45 min. respectively.

(Modified from Ghai, Rao and Batra, 1985 a).

On average, dry matter accumulation was 2.3g per plant and N content 3.5%. There were, on the average, 36 nodules/plant weighing 92 mg dry weight. In all the strains, nodulation was profuse even in the uninoculated controls and the nodules were mostly confined to the tap root. The intense pink colour of the nodules suggested their active nitrogen fixing ability. The rhizobia corresponding to *S. sesban*s were thus already present in abundance in the alkali soil. In the competition studies based on antibiotic marker patterns, it was found

that the native strains competed actively and prevented nodulation by effective strains of the inoculated Rhizobium sp.

### Salinity and alkali tolerance at germination

Response to different levels of salinity at germination was studied up to 10 days. There was no effect on germination up to EC 11 mmhos cm<sup>-1</sup> (0.7 % salt concentration) beyond which there was a drastic reduction (Table 2) at EC 15 (1% salt) and EC 18 (1.2% salt).

TABLE 2: Effect of salinity and alkalinity on germination of S. sesban

Salinity (mmhos cm <sup>-1</sup> )	Days			Alkalinity (pH)	Days		
	1 %	5 germination	10		1 %	4 germination	7
Control	78.0	100	100	Control	47.5	84.2	84.2
5	40.2	94.7	100	8.0	52.6	88.2	91.1
11	3.9	68.6	97.5	9.0	60.5	99.0	99.0
15	1.2	27.3	67.4	10.0	48.6	92.2	92.2
18	0	7.8	24.6	11.0	7.9	39.6	60.5

(modified from Ghai, Rao and Batra, 1985 b).

This agrees well with Jen et al. (1965) who reported that S. aegyptiaca (Syn. S. sesban) tolerated a salt concentration of 0.4–1.0% at seedling stage. S. sesban was subjected to alkalinity stress up to 7 days. Increase in alkalinity up to pH 9.0 had a beneficial effect. Maximum germination took place at pH 9.0, however it could tolerate pH 10.0. Beyond this, there was a decrease as well as delayed germination. Kumar (1983) showed that germination of S. aegyptiaca is unaffected up to a soil pH of 9.4 beyond which there was reduction. The plants could tolerate even pH 9.9, showing 72% germination as compared to germination in a normal soil of pH 7.6.

Successful establishment of a seed-propagated tree species in salt-affected soils depends on its capacity to initiate and complete the germination process since this phase is often relatively more sensitive, and often more decisive than subsequent growth stages. The results of the present study and that of the earlier ones show that S. sesban germinates quickly, has a high survival rate and is quite tolerant to salinity and alkalinity.

### Green-manure potential and biomass accumulation (Short-term study)

At 100 days growth stage, 10 kg seed rate ha<sup>-1</sup> was optimal as it resulted in maximum height (2.3 m) and girth (14 mm) of the plants and produced maximum biomass (oven-dry), 5.2 t ha<sup>-1</sup> (Table 3). The total N, P and K and S accumulation was 84, 7.2, 7.5 and 17.2 kg/ha of which the green manure potential was 68 kg N, 4.9 kg P and 53 kg K and 11.4 kg S, respectively per hectare (Table 4).

TABLE 3: Biomass accumulation in S. sesban (100 days growth)

Seed rate (kg/ha)	Height (m)	Girth (mm)	BIOMASS t.ha <sup>-1</sup>			
			Stem		Leaf	Total
			Upper	Lower		
5	1.8	12	0.6	1.2	0.6	2.4
10	2.3	14	1.4	2.5	1.3	5.2
15	2.1	11	1.2	2.1	1.0	4.3
20	1.8	9	1.3	2.4	1.1	4.8

TABLE 4: Nutrient accumulation (kg/ha) in S. sesban at 100 day growth.

Seed rate (kg/ha)	Leaf				Stem (Upper)				Stem (Lower)				Total				Total
	N	P	K	S	N	P	K	S	N	P	K	S	N	P	K	S	
5	25	1.6	15	3.5	6	0.7	9	1.7	8	1.1	10	2.8	39	3.4	34	8.0	84.
10	55	3.4	33	7.5	13	1.5	20	3.9	17	2.3	22	5.8	85	7.2	75	17.2	184.
15	42	2.6	25	5.8	11	1.3	18	3.4	14	1.9	18	4.8	67	5.8	61	14.0	147.
20	46	2.9	28	6.4	12	1.4	19	3.6	16	2.2	21	5.5	74	6.5	68	15.5	164.

At 200 days the plants grew to an average height of 3.2m, girth 17mm and produced a biomass (oven-dry) of 12.7 t ha<sup>-1</sup> of which the stem contributed 12.1 (Top 2.6, middle 3.7, bottom 5.8) and leaves 0.6 t ha<sup>-1</sup>. The differences among the various seed rates were non-significant. The total N, P, K and S accumulation at 200 days was 120, 9.2, 117 and 17.7 kg ha<sup>-1</sup> of which the green-manure potential was 59 kg N, 4.1 kg P, 38 kg K and 7.9 Kg S ha<sup>-1</sup> (Table 5).

TABLE 5: Nutrient accumulation (kg ha<sup>-1</sup>) in S. sesban at 200 days growth (average of seed rates)

Plant Part	N	P	K	S	Total
<u>Leaf</u>	32	1.8	10	4.0	47.8
<u>Stem</u>					
Top	27	2.3	28	3.9	61.2
Middle	27	2.1	33	5.2	67.3
Bottom	34	3.0	46	4.6	87.6
<u>Total</u>	120	9.2	117	17.7	263.9

### **Biomass accumulation (Long-term study)**

*Sesbania sesban* grew to an average height of 7 m (range, 5.2 m to 8.2 m) and girth of 58 mm (range, 32-80 mm) in the alkali soil. Biomass production (air-dry) was 87.0 t ha<sup>-1</sup>. Height and girth increments measured during the experiment showed that there was no appreciable growth after two years.

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### 3. NITROGEN FIXATION IN CASUARINACEAE

G.D. BOWEN<sup>1,2</sup> AND PAUL REDDELL<sup>1</sup>

(1) Division Soils, C.S.I.R.O., P.M.B. 2, Glen Osmond, South Australia 5064, Australia.

(2) Joint FAO/IAEA Division, Wagramerstrasse 5, P.O.B. 100, A-1400 Vienna Austria.

#### SUMMARY

Some 29 species of Casuarinaceae are now known to nodulate. Although species of Casuarina were usually well nodulated in the field, nodulation of Allocasuarina was variable and often absent. Frankia sources from Casuarina usually nodulated other Casuarina species; similarly cross-inoculation was frequent with Allocasuarina but there was little cross-inoculation between genera. Large differences in effectiveness of Frankia-Casuarina combinations occurred - some Frankia highly effective on C. equisetifolia were ineffective on C. cunninghamiana and vice versa. Inoculation of each species of Casuarina with selected Frankia strains is necessary for effective nitrogen fixation.

Soil temperature affected growth of C. cunninghamiana differently when dependent on the symbiosis than when given fertilizer nitrogen. Nitrogen fixation did not occur below 20°C. Soil phosphate status was important in determining distribution of Allocasuarina and Casuarina and in nodulation and nitrogen fixation. Interactions with mycorrhizal fungi in uptake of phosphate (and other nutrients necessary for plant growth or nitrogen fixation processes) are discussed.

Frankia sources differed in their tolerance of high soil salinity. Selection of Frankia for highly saline soils is likely to be important to Casuarina growth in such soils.

Future directions for nitrogen fixation research and management are discussed.

#### INTRODUCTION

The symbiotic fixation of atmospheric nitrogen by Frankia (an actinomycete) in root nodules formed on Casuarinaceae is a key factor in the successful growth of these trees and shrubs in a wide variety of nitrogen deficient soils in warm temperate and tropical climates. With fast growing species such as Casuarina equisetifolia\*, Dommergues (1963) calculated at least 58 kg N ha<sup>-1</sup> yr<sup>-1</sup> were fixed and it is apparent both from this and from laboratory studies that fixation rates can approach those of effectively nodulated legumes. If members of the Casuarinaceae are to achieve their full potential in production of fuelwood, in soil conservation, in soil rehabilitation, and in bestowing productivity on saline soils, it is important to understand the biological and environmental factors affecting the symbiosis. This paper addresses some of these.

## BIOLOGICAL FACTORS

### Occurrence of Nodulation

Some 29 of the 68 species of Casuarinaceae have now been recorded as nodulating (Bond, 1976; Lawrie, 1982; Reddell, Bowen and Robson, 1986). It is highly probable that some do not nodulate but as the absence of nodulation in the field may reflect only the absence of an appropriate *Frankia*, or soil conditions unsuitable for nodulation of the particular species, dogmatic conclusions on non-nodulation cannot be drawn. Certainly, there are large differences in the ease and the extent of nodulation between genera and species in the Casuarinaceae (Lawrie, 1982; Reddell et al, 1986). In a study of 187 Australian sites, embracing 22 species of Casuarinaceae, Reddell et al, (1986) found most plants of the four *Casuarina* species examined were nodulated at the 60 out of 88 sites. However, with only 5 of the 17 species of *Allocasuarina* examined (120 sites) did nodulation occur in more than 50 % of the sites - nodulation was not observed with 8 species (2 to 9 sites per species). Furthermore, in no species of *Allocasuarina* was more than 40% of the individual plants nodulated (see also Lawrie, 1982.)

*Allocasuarina* was particularly frequent in soils with low available phosphorus; 70% of all sites carrying *Allocasuarina* has less than 5 ppm available phosphorus, while only 42% of *Casuarina* sites were in this category. Subsequent glasshouse studies indicated that two of the major factors determining field nodulation were the presence/absence of appropriate *Frankia* and soil phosphate status, although other factors such as low soil pH undoubtedly are important also (Bond, 1957; Coyne, 1973).

Why is the variation in frequency of nodulation *Allocasuarina*, (both between sites and within sites) so marked? Perhaps *Allocasuarina* species consist of mixed populations of individuals that are susceptible and resistant to *Frankia* infection (a hypothesis which could be tested via vegetative propagation from individual plants) or perhaps nodulation of this genus may be particularly sensitive to small variations in site conditions. Because of this frequently poor nodulation it should not be assumed that the contribution of casuarinas to the nitrogen economy of a natural ecosystem is always large.

### Specificity in Nodulation

Very few pure cultures of infective *Frankia* have been isolated from *Casuarina* nodules so far, and inocula used in studies on specificity have necessarily been a suspension from a crushed nodule (usually raised from a single nodule on plants in sterile soil). As nodules may sometimes contain more than one strain of *Frankia* (Reddell and Bowen, 1985, a), results from such studies on specificity will need to be confirmed by later studies using a range of pure cultures of *Frankia*. There is no evidence that *Frankia* which form nodules on other actinorhizal plants (eg. *Alnus*, *Myrica*) also nodulate *Casuarina*. Some specificity in nodulation within the Casuarinaceae was indicated by Coyne (1973). Reddell and Bowen (1985, b) using nodules from 25 species of *Casuarina* and 11 species of *Allocasuarina* to inoculate 8 and 6 species of *Casuarina* and *Allocasuarina* respectively, found very high cross-inoculation within *Casuarina* and frequent (but less) cross inoculation within *Allocasuarina* but little cross inoculation between these genera. Some *Frankia* had wider host ranges than others, nodulating outside the genus or series of origin; in particular, 3 sources from *A. torulosa* provided 7 of the 10 instances in which *Allocasuarina* sources

formed nodules on Casuarina, and thus may be a bridging species. With Casuarina there appeared to be no barriers between series, and while this was probably the case also with Allocasuarina, the data were too few to be certain.

### Effectiveness

To examine whether different Frankia-Casuarina combinations differed in effectiveness, Reddell and Bowen (1985, c) inoculated C.equisetifolia ssp. incana and C.cunninghamiana, (both of which are important species in a number of developing countries) with five different sources of Frankia. This glasshouse study showed striking differences between Frankia-Casuarina combinations in their effectiveness (Table 1).

Although strain cb nodulated C.equisetifolia profusely it was completely ineffective but was easily the most effective of this species on C.cunninghamiana; strains kb, and ca, although highly effective on C.equisetifolia either did not nodulate C.cunninghamiana (kb) or were poorly effective (ca).

TABLE 1. The effects of 5 Frankia sources on growth, nodule formation and nodule activity with C. equisetifolia and C.cunninghamiana; 240 days after sowing (Reddell and Bowen),

Inoculum Source*	Plant Species <sup>†</sup>	Shoot Dry Wt (g)	No. Nodule per Plant	Nodule d. wt per plant (mg)	N fixed g <sup>-1</sup> nodule
kb	EQU	1.55	49	117	0.38
	CUN	0.00	0	0	-
ca	EQU	1.39	94	146	0.23
	CUN	0.70	41	104	0.14
hw	EQU	0.19	73	63	0.06
	CUN	0.07	0	0	-
ch	EQU	0.38	108	98	0.9
	CUN	0.08	0	0	-
cb	EQU	0.11	66	22	0.03
	CUN	2.27	19	195	10.03
Uninoculated	EQU	0.10	0	0	
	CUN	0.11	0	0	

\* Sources kb, ca, hw, were from C.equisetifolia, ch was from C.timorensis cb, was from C.cunninghamiana

+ EQU = C. equisetifolia, CUN = C. cunninghamiana

These results are of great applied significance:

(i) they indicate that Frankia strains must be selected to match the particular species one wishes to introduce, in order to maximise tree growth. Perhaps some failures with casuarinas are due to the lack of inoculation with a suitable Frankia - we have observed instances of this. At present, a Frankia selection programme with 10 species of casuarinas is in progress in our laboratory. It may be that effectiveness groupings will emerge ie. clusters of species for which the one Frankia may be effective on all.

(ii) they raise the possibility that in some places where casuarinas have been introduced (successfully), the existing Frankia strains may be of only moderate effectiveness. In such cases problems may occur with the introduction of more highly effective strains. One of our programmes (sponsored by the Australian Centre for International Agricultural Research in collaboration with the Royal Thai Forest Department), is to examine the relative effectiveness of Frankia nodulating C. junghuhniana in the many locations in which this species has been planted in Thailand.

(iii) In many natural Australian woodland ecosystems, productivity is determined largely by soil nitrogen (and soil phosphorus) status. In many cases the major accession of nitrogen is from casuarinas and it is likely that the productivity of the ecosystem (and the rate of successional development) will be determined largely by the effectiveness of the indigenous Frankia strains.

In the study above, all sources of Frankia formed nodules at similar times and differences in effectiveness were not due to this. Table 1 shows that "effectiveness" was a function both of total nodule weight and of nitrogen fixed  $g^{-1}$  nodule. With the ineffective cb - C. equisetifolia combination, high numbers of small nodules and low fixation efficiency occurred; with the cb - C. cunninghamiana combination, low numbers of large nodules with high fixation rates occurred; other pairings showed a mixture of these properties. The nature of high/low fixation  $g^{-1}$  nodule remains to be studied - is low fixation efficiency due to a low fixing activity per Frankia cell in the nodule or is it merely that there are relatively few Frankia cells in the nodule?

## ENVIRONMENTAL FACTORS

Many edaphic and climatic factors can affect nitrogen fixation, either directly by their effects on establishment of the infection, the various stages leading to nitrogen fixation, and the physiology of symbiosis or indirectly by effects on plant growth and assimilates available to the nodule. Below, we give three examples of environmental effects on nitrogen fixation.

### Soil Temperature

Table 2 (from Reddell, Bown and Robson, 1985) shows the effect of differing soil temperatures on C. cunninghamiana growth when dependent on nitrogen fixation and when supplied with nitrogenous fertilizer ("applied N"), and on nodulation and nitrogen fixed  $g^{-1}$  nodule.

(i) Reasonable growth occurred at 15°C soil temperature when plants had N applied, but when dependent on N-fixation, no response occurred until

20°C. Furthermore, the optimum soil temperature for growth with applied N was 20°C, but with the symbiotic system it was 25°C. These data indicate that the physiology of the interacting soil/micro-organism/plant system is markedly different in many respects from the "simple" soil/plant system. In many soils, casuarinas are dependent almost entirely on nitrogen fixation, and factors such as soil temperatures at times when soil moisture is adequate for plant growth must be considered in site/casuarina species/Frankia selection. Reddell *et al.* (1985) suggested that the sensitivity of the symbiotic system to soil temperatures below 20°C may define the limits to the natural distribution of C.cunninghamiana and other Casuarina species. It will be necessary to perform screening programmes to select highly effective Casuarina species-Frankia combinations at soil temperatures relevant to the areas to be planted.

TABLE 2: Effect of soil temperature on shoot and nodule dry weights/of Casuarina cunninghamiana, and N fixed g<sup>-1</sup> nodule Means  $\pm$  S.E. mean (Reddell, Bowen and Robson, 1985) 148 days.

N Treatment	Soil temp (°C)	Shoot D.Wt g/plant	Nodule D.Wt mg/plant	g N g <sup>-1</sup> nodule
Nil	15-30	0.05 <sup>±</sup> 0.01	0	
NH <sub>4</sub> NO <sub>3</sub>	15	0.97 <sup>±</sup> 0.10	0	
	20	2.13 <sup>±</sup> 0.67	0	
	25	1.27 <sup>±</sup> 0.70	0	
	30	1.15 <sup>±</sup> 0.24	0	
Frankia cb	15	0.04 <sup>±</sup> 0.01	3 <sup>±</sup> 1	-
	20	1.57 <sup>±</sup> 0.27	181 <sup>±</sup> 34	0.35 <sup>±</sup> 0.10
	25	2.57 <sup>±</sup> 0.18	307 <sup>±</sup> 75	0.30 <sup>±</sup> 0.06
	30	0.80 <sup>±</sup> 0.13	65 <sup>±</sup> 8	0.37 <sup>±</sup> 0.02
Frankia tn	15	0.03 <sup>±</sup> 0.01	1 <sup>±</sup> 0.4	-
	20	0.34 <sup>±</sup> 0.13	34 <sup>±</sup> 9	0.11 <sup>±</sup> 0.01
	25	1.33 <sup>±</sup> 0.23	133 <sup>±</sup> 27	0.35 <sup>±</sup> 0.11
	30	0.81 <sup>±</sup> 0.15	75 <sup>±</sup> 26	0.33 <sup>±</sup> 0.05

(ii) Short-term studies on nitrogen fixation by excised Casuarina

nodules have demonstrated an optimum temperature of 35°C (Waughman, 1977) for nitrogen fixation. The studies above (with a different species) indicating a 25°C optimum with the whole plant system, suggests a danger in extrapolating from studies on excised nodules to whole plants and to field situations. The main determinant of the optimum soil temperatures and other "climatic factors" for fixation may be via effects on the plant assimilation of CO<sub>2</sub> and its translocation to the root.

(iii) The effects of soil temperature on fixation (Table 2) were largely on nodule development (which differed with Frankia source) and not on the fixation process itself, although with Frankia source in the nitrogen fixation g<sup>-1</sup> nodule was also depressed at 20°C. Although some nodules formed with both strains at 15°C, these were small and fixed little, if any, nitrogen.

### Soil Nutrients

As for legume nitrogen fixation, some elements eg. molybdenum may be needed uniquely or in relatively greater supply for nitrogen fixation than for plant growth and assimilation. The resolution of plant v. nitrogen fixation requirements has been discussed by Robson (1983) in relation to legumes. Table 3 from Diem and Gauthier (1982) indicates the importance of mycorrhizal infection. Bond and Hewitt (1962, 1967) have shown the necessity of Co and Cu for the fixation process in Casuarina. Mo is probably also necessary.

TABLE 3: Inoculation of seedlings of C.equisetifolia with Frankia nodules and/or an endomycorrhizal fungus (Glomus mosseae) (Diem and Gauthier, 1982) (6 months)

Treatments	Nodule		P L A N T	
	Dry wt mg/plant	Dry wt g/plant	Total N mg/plant	Total P mg/plant
Control	0 <sup>a</sup>	2.69 <sup>a</sup>	22.0 <sup>a</sup>	2.6
+ <u>Frankia</u>	57 <sup>b</sup>	4.23 <sup>b</sup>	50.7 <sup>b</sup>	2.1 <sup>b</sup>
+ <u>Frankia</u> + mycorrhiza	132 <sup>c</sup>	7.69 <sup>c</sup>	96.1 <sup>c</sup>	3.9 <sup>c</sup>
+ <u>Frankia</u> + Phosphate	107 <sup>c</sup>	7.49 <sup>c</sup>	120.5 <sup>c</sup>	3.0 <sup>b</sup>

Values in columns having the same letter superscripts differ with probability = 0.01 (Duncan test)

Soil phosphate status has a central role in distribution of casuarinas - Reddell et al (1986) found Casuarina occurred much more frequently than Allocasuarina on sites with more than 10 ppm bicarbonate available phosphate (see above). Frequently, species of Casuarina are much faster in growth than Allocasuarina and it is apparent that small additions of phosphate to a soil may allow the successful introduction of much faster growing species.

**Mycorrhizas and cluster roots** Mycorrhizal infections of roots (which occur with most of the higher plants) and microbial stimulation of root branching on a few plant families ('cluster' or 'proteoid' roots, Lamont, 1982) (Malajczuk and Bowen, 1974) are particularly important in increasing the absorption of poorly mobile ions from soil.

Although mycorrhizas may increase the uptake of many such ions eg. Zn, K, Cu, Mo (see Bowen, 1980), phosphate uptake has received particular attention, and indeed occupies a special place, not only because phosphorus and nitrogen are the most frequently deficient nutrients in soils but also because high phosphate levels depress mycorrhiza formation. Certain root characteristics such as an abundance of fine roots with well developed root hairs (eg. with gramineous plants) assist in effective uptake of poorly mobile ions from soil, but root microbial associations have almost always been involved also in the evolution of root systems to cope with nutrient deficient soils. Mycorrhizas are also important in competition between species for nutrients and have probably been important in the evolution of mixed ecosystems (Bowen, 1980).

In 83 Australian soils examined by Reddell *et al* (1986), casuarinas at only 14 sites had neither mycorrhizas nor cluster roots. Cluster roots, ectomycorrhizas and vesicular-arbuscular mycorrhizas (V.A.M.) (the two major mycorrhiza types, encompassing the vast majority of higher plants) occurred both on *Casuarina* and *Allocauarina*, frequently on the same plant. Cluster roots were relatively uncommon. Ectomycorrhizas were most frequent with *Allocauarina* and V.A.M. dominated somewhat in *Casuarina*. Table 3 indicates the importance of mycorrhizas to phosphate uptake and thence to nitrogen fixation - it is little wonder that casuarinas are pioneer plants *par excellence*. Little is known, so far, about the specific mycorrhizal requirements for casuarinas.

The technology of inoculation with ectomycorrhizal fungi has now been worked out (see Theodorou, 1971; Marx *et al*, 1982). V.A.M. cannot yet be grown in laboratory media and the logistics of large scale inoculation with direct sowing of agricultural crops, are daunting. However, inoculation of forest nurseries with selected V.A. fungi should be practicable. There are exciting possibilities ahead.

Many other soil "chemical" factors will probably affect nodulation and nitrogen fixation eg soil pH, (Coyne, 1973) and levels of soil nitrogen. Such factors have yet to be studied in detail. It is probable that there will often be mycorrhizal interactions in those factors - Bowen (1980, 1985) pointed out that growth of mycorrhizal fungi into soil should be regarded as a general alternative root strategy, and that such growth by selected mycorrhizal fungi will often compensate for poor root growth in deleterious soil situations, eg high soil acidity, high aluminium and highly saline soils and where root disease organisms occur. That is, the plant scientist has two genomes to manipulate, not just one.

### Soil Salinity

Some casuarinas grow in extreme soil situations, one of which is high soil salinity. For example, *Casuarina obesa* occurs naturally (and is nodulated) in soils with up to  $28 \text{ mg C}^{-1} \text{ g}^{-1} \text{ soil}$  (28,000 ppm). Several other species also grow in saline soils or in sites where they would be subject to considerable cyclic salt eg *C. glauca*, *C. equisetifolia*.

Reddell, Foster and Bowen (1986) examined the effect of salinity on nodule growth and nitrogen fixation with two Frankia sources. Table 4 shows a quite different effect of increasing salinity on fixation by these two Frankia: the less effective strain (cb) had greatly impaired nitrogen fixation beyond 0.15 mg NaCl g<sup>-1</sup> soil but strain ys was unaffected at 10 times this concentration. Decreased nitrogen fixation occurred via an effect on nodule growth (both strains) and via fixation g<sup>-1</sup> nodule. (cb only). Electron microscopy showed that with strain ys, nodule cells containing Frankia has very little chloride accumulation, and it is possible that with some Frankia-Casuarina combinations, physiological/anatomical changes occur in the cell wall/plasmalemma which exclude chloride. In a parallel (unreported) study uninoculated C.obesa supplied only with fertilizer N grew only in much lower salt concentrations that those infected with Frankia ys; this needs further study.

TABLE 4: The effect of increasing soil NaCl concentration on N content in shoots, nodule dry weight and N<sub>2</sub> fixation in Casuarina obesa seedlings inoculated with two sources of Frankia (<sup>±</sup> SE) 24 weeks after inoculation, 16 weeks after the commencement of salinity treatments. (Reddell, Foster and bowen, 1986).

<u>Frankia</u> source	NaCl added mg NaCl g soil <sup>-1</sup>	Nitrogen content of shoots	Dry weight of nodules mg pot <sup>-1</sup>	mg shoot per mg nodule mg pot <sup>-1</sup>
ys	0	126 <sup>±</sup> 5	550 <sup>±</sup> 23	0.23 <sup>±</sup> 0.01
	0.15	190 <sup>±</sup> 4	562 <sup>±</sup> 48	0.35 <sup>±</sup> 0.02
	1.5	109 <sup>±</sup> 32	292 <sup>±</sup> 55	0.37 <sup>±</sup> 0.04
	15	17 <sup>±</sup> 3	57 <sup>±</sup> 14	0.30 <sup>±</sup> 0.03
cb	0	30 <sup>±</sup> 5	203 <sup>±</sup> 48	0.15 <sup>±</sup> 0.03
	0.15	32 <sup>±</sup> 6	176 <sup>±</sup> 62	0.18 <sup>±</sup> 0.05
	1.5	8 <sup>±</sup> 3	123 <sup>±</sup> 37	0.07 <sup>±</sup> 0.02
	15	1	25 <sup>±</sup> 2	-

It is clear that selection of salt tolerant Frankia strains will have an important bearing on the use of casuarinas to bestow productivity on highly saline soils. Such soils could well be important fuelwood producing sites for many developing countries.

## FUTURE DIRECTIONS

We have indicated above some of the plant/*Frankia* factors and environmental factors which affect nitrogen fixation and play a critical role in the successful growth of casuarinas. Below, we comment briefly on some future research needs in the management of nitrogen fixation by casuarinas.

We have demonstrated specificity both in nodule formation and in effectiveness and therefore the need for *Frankia* selection and inoculation programmes. Both of these activities will be assisted enormously by the development of methods for the easy isolation and growth of *Frankia* nodulating the Casuarinaceae. At present this is difficult, not impossible (eg Diem, Gauthier and Dommergues, 1982; Zhang, Lopez and Torrey, 1984). Inoculation technology, to date, has used crushed nodules as inoculum; this will change drastically in the next few years. With isolation and cultivation of *Frankia* from casuarinas, not only will highly efficient inoculum production and application technologies be developed, but also sound research on *Frankia* strain identification and *Frankia* ecology will be possible.

Environmental effects on fixation have obvious important consequences. It is appropriate to further examine soil factors such as those above, in order to appreciate the critical steps being affected. In order to manage N fixation more effectively, either by *Frankia* selection or site management, good methods must be developed for studying the effect of environment on growth of *Frankia* in the rhizosphere, the infection process, nodule genesis, nodule development and nitrogen fixation processes. Nodulation/nitrogen fixation can fail at any of these.

The measurement of nitrogen fixation in the field, and questions such as the rate of nitrogen availability to associated plants are further areas requiring study. "Traditional" methods used in glasshouse studies: plant growth responses in closed pots, the use of  $^{15}\text{N}$  gas or  $^{15}\text{N}$  isotope dilution methods, and acetylene reduction assay of nitrogenase activity have serious shortcomings in field conditions, partly because of losses from open systems, partly because of logistic and sampling problems associated with perennials ( $^{15}\text{N}$  dilution methods) and partly because such tests such as acetylene reduction give only one point in time (even if one could overcome problems of acetylene introduction into soil). Even with its faults (ie losses from the system), the best method so far has been the increase of nitrogen in the soil and the plant biomass at a field site (see Gauthier et al, 1978). "Newer" approaches to measurement of nitrogen fixation eg the use of  $^{15}\text{N}$  natural abundance (Rennie, Paul and Johns, 1976) have a particular attraction with perennials but this awaits critical examination.

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#### 4. A FRANKIA SOURCE SELECTION PROGRAMME TO IMPROVE NITROGEN FIXATION BY CASUARINACEAE

P. A. ROSBROOK

CSIRO Division of Soils, Private Bag No. 2,  
Glen Osmond 5064 AUSTRALIA

##### SUMMARY

1. A Frankia source selection program for select species of Casuarinaceae is outlined at both a glasshouse and field level.
2. Preliminary field results show a 30% increase in plant height due to inoculation at 16 months for one site and a negative response to inoculation at a second site.
3. The direction of future research is outlined.

##### INTRODUCTION

Various species within the family Casuarinaceae have potential for colonizing and stabilizing adverse soils. For example Casuarina equisetifolia commonly occurs on coastal sand dunes where it tolerates salt spray, infertile soils and drought. C.obesa has been observed to colonize highly saline soils whilst C.cristata grows well in extremely arid areas with as little as 200 mm annual rainfall.

Some 29 species within the family Casuarinaceae are known to be capable of entering into a symbiotic relationship with the actinomycete, Frankia. The symbiosis results in nitrogen being fixed in a similar manner to Legume-Rhizobium symbioses and in many instances the symbiosis is thought to be an important factor contributing to the successful establishment and growth of Casuarinas on adverse sites. However there is an urgent need to learn more about the symbiosis so that it can be successfully utilized and managed and so that the improvements to be gained by soils such as improved soil nitrogen and decreased soil erosion can be maximised.

Currently CSIRO, Division of Soils has a Frankia strain selection programme for 10 species of Casuarinaceae. The need for the programme arose from work by Reddell and Bowen (see 3) which showed that different crushed nodule sources varied in their ability to nodulate and fix nitrogen on two species of Casuarina. Further, a nodule source effective at fixing nitrogen on one species, could be quite ineffective on another species. Thus to optimize nitrogen fixation by Casuarina, it is necessary to select sources of Frankia effective at fixing nitrogen for the species in question.

##### FRANKIA STRAIN SELECTION

###### (1) Glasshouse and Laboratory Programme

The species included in the programme are listed in Table 1 along with data on their climatic range. The Frankia sources being screened include nodules from different species, climatic regions, and soils, and seven isolates.

TABLE 1: The 10 species being studied plus altitude and climatic data

Species	Alt (m)	Climatic zones*	Frosts /yr	Rainfall 50 percentiles	Season <sup>A</sup>
<u>C.cristata</u> subsp. cristata+	175-325	Wsa Wsh	2-50	550-650	U-S
<u>C.cunninghamiana</u> +	0-1000	Wsh Wsa	0-50	500-1500	S
<u>C.equisetifolia</u> var.+ <u>equisetifolia</u>	0-100	Hh Hsh Wsh	0	1000-2150	S
<u>C.equisetifolia</u> var. incana+	0-100	Wsh	0-3	100-1500	S
<u>C.glauca</u> +	0-30	Wh Wsh	0-5	900-1150	S
<u>C.junghuhniana</u> <sup>o</sup>	0-3000 m	Hh			S
<u>C.obesa</u> +	0-300	Wsh Wsa	0-12	250-500	W
<u>C.oligodon</u> <sup>o</sup>	-2,500 m	Hh			
<u>Allocasuarina decaisneana</u> +	250-700	A	1-12	200-250	U-S
<u>A.torulosa</u> +	0-1100	Wsh Wh	0-20	950-1250	S

\* A, arid; Wsa, Warm semi-arid; Wh, Warm humid; Wsh, warm sub-humid, Hh, Hot humid; Hsh, Hot sub-humid

A S, summer; W, winter; U, uniform

+ Climatic data from Doran, J.C. and Hall, N. (1983)

<sup>o</sup> Climatic data from National Research Council (1984).

The screening process commences in the glasshouse in a closed pot system in which plants are supplied with all essential elements except nitrogen. The questions addressed by the glasshouse trials are:

1. Which of the species of Casuarinaceae being studied are the Frankia sources capable of nodulating?
2. What is the relative effectiveness of the Frankia sources at fixing nitrogen when associated symbiotically with each species?

For most species, nodules are visible three to eight weeks after inoculation. Visible differences in plant growth as a result of different Frankia sources are evident by five months after inoculation.

In terms of growing up inoculum for large scale field work, crushed nodule inocula have many limitations, including extremely long time periods to grow up the quantity of nodules needed, and the lack of a method for assessing the viability of nodules. As a result, emphasis is being placed on isolation of Frankia from effective nodule sources. The first recorded isolation of a Frankia strain which was capable of re-infecting a species of Casuarina was that of Diem et al. (1983). Since then, further re-infective isolates have been reported from species of Casuarina (Zhang et al., 1984) and Allocasuarina (Zhang and Torrey, 1985). However, the total number of re-infective isolates is small. Work is currently underway to develop a routine procedure for isolation and thereby increase the number of Frankia isolates available.

## (2) Field Program

The field program aims to study the effect of inoculation and different Frankia sources on growth and nitrogen fixation by selected species of Casuarinaceae over a longer time period. Plants are raised in the nursery in tubes filled with a peat/vermiculite mix and fertilized with all essential elements except nitrogen. Inoculation takes place either when the seedlings are transplanted into tubes, or, immediately, prior to field planting, and involves watering on either a crushed nodule suspension or an isolate grown in liquid medium. Seedlings are planted into the field approximately six months after emergence.

Preliminary results are available for two field trials. The first trial involves C.cunninghamiana growing at a temperate site which is waterlogged during winter. At 16 months after planting into the field a 30% increase in tree height resulted from inoculation. Wood volume was calculated by using the formula for a cone and entering basal diameter and height measures. The 30% increase in height at 16 months was equivalent to a 180% increase in wood volume.

The second site is situated in the subtropics and consists of C.cunninghamiana supplied with three nitrogen sources (uninoculated, no applied nitrogen; uninoculated, applied nitrogen), each in the presence and absence of applied phosphorus. Plant height measures show that at 12 months after planting into the field, no response to nitrogen was obtained unless phosphorus was added. More importantly there was a negative rather than a positive response to inoculation. Further work is underway to ascertain what is preventing the nodulated plants from fixing nitrogen.

## FUTURE WORK

Future work will examine the effect of various soil and environmental factors on nodulation and nitrogen fixation. Production of inoculum for large scale use and methods of application in the nursery will also be studied.

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## 5. CURRENT STATUS OF MYCORRHIZA RESEARCH IN INDIA

DAVIS JOSEPH BAGYARAJ

Department of Agricultural Microbiology,  
University of Agricultural Sciences,  
G.K.V.K. Campus, Bangalore-560 065

### SUMMARY

- (1) Types of mycorrhizas and their importance in plant nutrition are briefly mentioned.
- (2) Mycorrhiza research in different laboratories in India is briefly reviewed.
- (3) Some areas where mycorrhizal associations may play a role in amelioration of soils are highlighted.
- (4) Possible areas for future research in mycorrhizal associations with trees, are suggested.

### INTRODUCTION

Mycorrhiza literally means 'fungus root'. Mycorrhiza results from a mutualistic symbiosis between roots and certain fungi. There are two main types of mycorrhizas; 1. Ecto and 2. Vesicular-arbuscular mycorrhizas. Ectomycorrhizas (EM) are mostly found in forest trees in the families Pinaceae, Salicaceae, Betulaceae, Fagaceae and Tiliaceae. Basidiomycetous fungi are the common fungal symbionts. Mycorrhizal associations stimulate branching of the roots. This along with fungal hyphae increases the absorption surface of the root. Some ectomycorrhizas are known to decompose organic matter. The ectomycorrhizal sheath also offers protection against root pathogens. EM fungi are culturable and some of them are produced industrially and available in the market in some countries of the world (Marx, 1980).

Vesicular arbuscular mycorrhizas (VAM) are commonly associated with most plants important in agriculture, horticulture and forestry. They are observed by clearing and staining roots, and looking for vesicles and arbuscules. VAM are produced by Zygomycetous fungi. They are obligate symbionts and hence maintained as "pot cultures" on suitable hosts. They improve plant growth through better uptake of P, Zn, Cu, water and making the root zone inimicable to root pathogens. They also improve the activity of N fixing organisms in the root zone. Plants respond well to inoculation with efficient strains of VAM even in unsterile soil with native endophytes (Manjunath et al., 1984). Recent studies show that VAM help in aggregation of soil (Bethlenfalvay, Personal communication). The bottleneck in VAM reaching practical agriculture is the inability to culture the fungus on laboratory media.

## REVIEW OF MYCORRHIZA RESEARCH IN INDIA

### University of Agricultural Sciences, Bangalore

In the Department of Agricultural Microbiology, work on VAM was initiated in the year 1977 by Dr. D. J. Bagyaraj. The work done so far brought out the following:

1. The occurrence of VAM in most of the economically important crops and trees, including reporting of their association for the first time in pepper, cardamom and betlevine.
2. Improved growth of crop plants and tree seedlings with VAM inoculation.
3. Isolation, screening and selection of efficient mycorrhizal fungi for citrus and leucaena.
4. Possibilities of increasing yield and/or saving phosphatic fertilizer application through VAM inoculation.
5. Suppression of the root pathogenic fungus Sclerotium rolfsii and rootknot nematode Meloidogyne spp. through VAM.
6. Synergistic interaction between VAM and rhizobia, azotobacters and phosphate solubilizing bacteria with consequential benefit to plant growth (Bagyaraj, 1984).
7. In a recent screening trial, Glomus mosseae was found to be the best mycorrhizal fungus improving the growth of 4 cultivars of Leucaena in a P deficient marginal soil.
8. Recently, 100 different species of tree seedlings growing in a marginal soil, were examined for mycorrhizal associations. About 60% of them were found to be colonized by VAM and the rest by EM. Aspects currently being investigated are:
  1. Mycorrhizal dependency of plants of economic importance,
  2. Microorganisms commonly associated with the pot cultures of VAM,
  3. Methods for producing 'clean' inoculum of VAM, and
  4. Response of tree species to EM and VAM inoculation.

### Forest Research Institute, Dehra Dun

Mycorrhiza research was initiated in 1950's under the leadership of Dr. B. K. Bakshi. Surveys to find out the occurrence of EM were carried out. The mycorrhizal fungi associated with different tree species were identified. In the nursery, fungicides were found to retard the growth of mycorrhiza only initially. Inoculation was found to reduce the nursery period of silver fir (Abies pindrow) from 6 growing seasons to 3 or 4. VAM association was observed in 8 conifers and 28 broad-leaved species and their spore population was more in summer. Two new species Glomus multicaulis and Sclerocystis sinnosa were reported (Bakshi, 1974).

### **Tropical pine research centre, Dehra Dun**

Dr. Thaper found that exotic conifers and hardwoods established mycorrhiza with native endophytes. Trimming of silver fir roots at the time of field planting considerably removed mycorrhiza. A survey for mycorrhiza in pine nurseries in different parts of the country suggested insufficient native ectomycorrhizal propagules in Indian soils. Pinus caribaea responded better to inoculation at acidic pH than at alkaline range. Glomus macrocarpum was the most common VA mycorrhizal fungus in forest soils (Thaper & Khan, 1985). Rate of destruction of mycorrhiza was more in poor, than quality sites. Fertilizers reduced VA mycorrhizal colonization in Kauri pine (Agathis robusta).

### **North Eastern Hill University, Shillong**

Prof. R.R. Mishra and his group are studying the ecology of mycorrhizal associations in timber trees, weeds and orchids, and the role of mycorrhiza in plant nutrient uptake.

### **Delhi University, New Delhi**

Prof. K.G. Mukerji has established an excellent school on fine structure and taxonomy of VAM. The laboratory is also involved in the studies of VAM spores (Mukerji and Ardey, 1985).

### **Jawaharlal Nehru University, New Delhi**

Dr. A.K. Varma investigating the VAM of Aravally hills and xerophytes reported Melia azadirachta harboured Gigaspora sp. in the root system, while Ficus bengalensis and Murraya paniculata harboured Glomus sp. thus showing host preference by these fungi. A new species Gigaspora coralloidea occurring in xerophytes was reported from this laboratory. Surface sterilized Glomus macrocarpum spores were found to harbour enteric bacteria, pseudomonads and streptococci (Varma et al., 1981).

### **Haryana Agricultural University, Hissar**

Dr. B.L. Jalali, surveying soils of Haryana for VAM, observed more root colonization and spores in nutrient deficient soils. Inoculation of plants with efficient strains of VAM improved growth and P uptake. Addition of rock phosphate with VAM further improved plant growth. Fungitoxicants Brassicol, Emisan, Bavistin and Thirma depressed VAM. VAM reduced the severity of disease caused by the root pathogens Fusarium oxysporum and Rhizoctonia solan. Dual inoculation with Rhizobium and VAM improved nodulation, N fixation and plant growth in legumes (Jalali and Thareja, 1985).

### **Govind Ballabh Pant University of Agriculture and Technology, Pantnagar**

Dr K. Seetharamaiah of this Institute has carried out extensive studies on interaction between VAM and root knot nematodes. A time course study confirmed that mycorrhizal colonization begins 1-3 days after inoculation and reaches a maximum within 3-4 weeks. Optimum inoculum level needed for growth improvement was 200 spores/plant and adding inoculum at the planting hole was found to be better than mixing the inoculum with entire soil.

### **Indian Agricultural Research Institute, New Delhi**

Dr. N.S. Subba Rao and his associates have recently started studying the interaction between VAM and N fixing bacteria, especially Azospirillum. Synergistic interaction between the two organisms was observed.

### **International Crops Research Institute for Semi Arid Tropics, Hyderabad**

Dr. K. Krishna observed plant genotype dependent differences in VAM colonization. Different plant genotypes within a single species varied in their ability to harbour VAM. This suggests that during breeding programmes, inheritance patterns of VAM colonization may be worth looking at (Krishna et al., 1984).

### **Tamil Nadu Agricultural University, Coimbatore**

Dr. Kandaswamy and Mr. Santhanakrishnan are studying growth responses of species to VAM inoculation. Other areas of study include: 1. Interactions of VAM with other beneficial soil microbes, 2. Biological control of soil-borne diseases using VAM, 3. Possibilities of reducing P-fertilizer application through VAM inoculation.

### **Sri Pushpam College, Poondi**

Prof. K. Kannan and his associates have initiated studies on EM and VAM. Recently they observed VAM in some rhizomatous medicinal plants of Zingiberaceae and Araceae.

### **Sheep Breeding Research Station, Sandynallah**

Mr. R. Narayanan isolated EM fungi associated with Pinus patula plantations in Nilgiris and Palani hills. Amanita muscaria, Laccaria laccata, Hebeloma crustuliniforme, Rhizopogon sp. and Suillus sp. were found to be the common mycorrhizal associates. Results from the mycorrhiza synthesis and nursery inoculation studies showed Pisolithus tinctorious to be the best mycorrhizal fungus of EM with pesticides and methods for mass production of P.tinctorious are in progress (Narayanan & Bhattacharyya, 1984).

### **Central Plantation Crops Research Institute, Kasargod**

Dr. C. R. Ramesh and Dr. Rohini Iyer who are investigating the mycorrhizal associations in plantation crops have found Endogone australis and Gigaspora gilmori to be the two dominant fungal associates. Coconut, cacao, cinnamon and black pepper were the crops examined. Spores were abundant in poor soils and younger roots showed higher percentage root colonization (Ramesh, 1984). From the Kayangulam centre, Dr. V. G. Lily reported the occurrence of mycorrhiza in coconut for the first time.

### **Central Agricultural Research Institute, Port Blair**

Dr. Ramesh has recently initiated VAM research in Port Blair. He is screening for efficient strains of VAM to be used as inoculants for oil palm. VAM as a bio-control agent is also being investigated.

## **SOME AREAS WHERE MYCORRHIZA MAY PLAY A ROLE IN THE AMELIORATION OF SOILS**

### **Revegetation of strip mines and other industrial waste lands**

Legumes are a special case from the point of view of plant ecology as they can be supplied with N and P by the naturally existing symbionts, Rhizobium and VAM. Therefore plants colonizing mine spoils and other industrial wastelands are usually legumes, indicating the importance of VAM for revegetation purposes in these soils.

### **Establishment and improvements in marginal soils**

Tropical soils are highly P deficient. Mycorrhizae have the ability to scavenge a larger volume of soil beyond the P depletion zone and absorb P from concentrations much lower than that which can be absorbed by the root hairs. Thus they help in the introduction of legumes to nutrient deficient soils and thereby bring about improvement of these soils.

### **Reclamation of eroded soils**

Loss of top soil and vegetation is a consequence of erosion. Eroded soils tend to be depleted of VAM. Reintroduction of these fungi help in the establishment of plants and also improve soil structure, thereby reducing soil erosion (Powell, 1980).

### **Tolerance to other stress situations**

Mycorrhizal plants have a high tolerance to salinity, low pH, and soil temperature (Lambert & Cole, 1980). Mycorrhizal plants are also known to tolerate water stresses and transplant shock better than non mycorrhizal plants (Menge et al., 1978).

### **Decomposition of litter and direct cycling of nutrients**

Ectomycorrhizal fungi have been reported to play a role in the decomposition of organic matter and in the direct nutrient cycling (Smith, 1980).

### **Transport of nutrients between trees**

A network of mycorrhizal mycelia may link one tree with the other thus transporting P between plants (Whittingham & Read, 1982). In leguminous trees, these hyphae may have a role in transporting N and P.

## **AREAS FOR FUTURE RESEARCH**

1. Selection of efficient strains of EM and VAM for the tree species important in soil amelioration.
2. Compatibility of EM and VAM with pesticides commonly used in forest nurseries.
3. Methods of inoculum production and inoculation.

4. In case of inoculation failures, follow up research to investigate reasons for failure.
5. Establishment of germplasm collection centres of mycorrhizal fungi.
6. Mycorrhizal dependency of forest tree species.
7. Dual inoculation of VAM and N fixers such as Rhizobium and Frankia in tree species.
8. Role of mycorrhiza in biological control of soil borne pathogens in the forest tree nursery.
9. Possibilities of introducing VAM through trees in alley cropping systems advocated in agro-forestry which will act as sources of mycorrhiza for crop plants sown season after season.

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## CHAPTER V

### LAND USE PRACTICES FOR AMELIORATION OF SOILS BY TREES.

It is clear that there is little point investigating soil ameliorative properties of trees without considering the implementation of these processes into practical management systems.

Which land use systems are most suited to incorporation of trees to improve soil productivity?

P Robinson in Section 1, leaves us with little choice. His review of the trends in supply and demand of crop, livestock and wood products shows that demand for each of these resources will soon outstrip supply. The expansion required in production of each of these resources must be at the expense of reduction in others due to the further deterioration of suitable land. He shows that these resource production systems are interrelated. This suggests that agroforestry, a land use system which can combine production of all three, is a suitable land use system for implementation of soil amelioration by trees.

The potential of agroforestry as a practical management method for sustaining soil fertility is examined in more detail by A Young in Section 2.

Case studies of two agroforestry systems are described by Handawela and Jama et al. The potential of maize cropping with Gliricidia maculata or with Leucaena leucocephala is examined for improvement of soil fertility and increased maize yields. The practical value of integration of trees with crops with respect to sustainable production is shown.

In Section 4, it is emphasised by M Douglas, that although it is clear that incorporation of trees into agricultural systems has potential for the improvement of soil productivity, such improved land use practices must be designed within the context of the people they are intended for. Lack of consideration of socio-economic constraints will probably result in failure of farmers to adopt such new and improved management methods.

**THE DEPENDENCE OF CROP PRODUCTION  
ON TREES AND FOREST LAND**

**Patrick J Robinson**

**Forest Research Project,<sup>+</sup> Department of Forests**

**Kathmandu, Nepal\***

**SUMMARY**

A number of studies have shown that in some situations cropland fertility and crop yields can be maintained by alley cropping systems which include mulch production by tree species. However, the great majority of crop production systems which are not sustained by application of artificial fertilizers continue to rely upon the import of nutrients (fodder, animal bedding, compost) from forest and other non-cultivated land. Trees on crop land also provide animal fodder, animal bedding and composting material.

Data from published sources are given to illustrate the importance of trees and forest land in supporting crop and animal production. The available data are often difficult to interpret and a plea is made for greater clarity in the presentation of data. The forest management and policy implications of the dependence of cropping systems on forest material are briefly discussed.

**INTRODUCTION**

Evidence from many parts of the world indicates that it is becoming harder and/or more expensive to maintain cropland soil fertility; in several countries crop yields are dropping, largely as a result of lowered soil fertility. Yet, with an expanding human population, the demands for crop, livestock and forestry products are increasing each year. High input (eg. artificial fertilizers) means of improving or maintaining soil fertility have often been inappropriate, particularly in the more marginal areas (eg. steep terrain, semi-arid lands) and for farming communities of low economic status. In the last decade the search for more appropriate means of sustaining soil productive capacity has intensified, and promising methods (both traditional and more recently developed) have been identified.

This review is restricted to those systems where trees and shrubs (from here onwards referred to collectively as trees) and forest land can play an important role in sustaining soil fertility and crop production. A critical evaluation of the evidence available on these systems should indicate the extent to which trees can contribute to improved sustainability, priorities for research, and ways in which Government policies may encourage promising systems of land husbandry.

<sup>+</sup>

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<sup>\*</sup>

Mailing Address: c/o FCO (Kathmandu), King Charles Street, London SW1A 2AH, United Kingdom

## **TRENDS IN SUPPLY AND DEMAND OF CROP, LIVESTOCK AND WOOD PRODUCE**

There is considerable interdependence between crop and livestock production (ILCA 1981, Bernstein *et al* 1983, FAO 1983 b, Robinson 1983) and these often rely substantially on resources from trees and forest land. A brief review of the world's trends in the supply and demand for crop, livestock and forest products helps to highlight the magnitude of the problems which a substantial proportion of the world's population is increasingly going to face in the future.

### **Forestry and Wood Products**

The Centre for Agricultural Strategy (CAS 1980), based on various figures published by FAO and The World Bank, suggested that by the year 2000 there is likely to be an annual deficit of about 8% of the total world wood demand, and by the year 2025, a 32% deficit. A number of assumptions were made to arrive at such predictions, including a doubling of yields from existing forests, and the cessation of destruction of natural forest. However, a doubling of yield may be difficult to achieve; further, the natural forest area was estimated to be declining by up to 16 million ha a year, an area much greater than that of new plantations being created annually (part of this loss of forest area is caused by the demand for new agricultural land, see below).

The demand for industrial wood products may be lower than predicted by the Centre for Agricultural Strategy, due to the general down turn in the World economy since the mid-seventies. However, the projections of fuel-wood and charcoal demand are likely to be realistic, since such demand is believed to be very inelastic. Fuelwood and charcoal demand are expected to make up about 40% of the projected demand for roundwood in the year 2000.

More recent studies, again largely based on FAO and UN figures, suggest that fuelwood deficits in the tropics will have more than doubled between 1980 and 2000, requiring a plantation area of over 100 million ha to meet the predicted deficit (Burley 1984). Yet the current annual rate of afforestation is only 1 million ha in the tropics.

Hence, in order to satisfy the need for wood products, the indications are that there should be a) No further reduction of forest and tree cover (and therefore no transfer to agricultural production); b) Increases in yield, which would necessitate improvements in forest management (including the management of livestock use of the forest) and c) Actual increases in the area planted to trees.

### **Crop Trends**

The absence of reliable data on overall cropland and crop production trends has handicapped efforts to assess the impact of mounting pressures on the world's croplands. Nevertheless, data exist from 1950 onwards for lands on which cereals are grown; cereals occupy 70% of the world's croplands and are the dietary staple of most societies (Brown 1978). Table 1 shows that the area capita<sup>-1</sup> under cereal crops has dropped since 1950 even with an increase of 26% in the area cropped; while with an estimated 10% increase in cropped area by the year 2000, the cropped area capita<sup>-1</sup> will be close to half that of 1950.

World cereal yields increased by 2.2% year<sup>-1</sup> from 1950 to 1970 and only by 1.5% year<sup>-1</sup> from 1970 to 1980 (Brown 1981). Not only has food production failed to keep up with population growth in more than half of the developing countries, but yields in a number of countries are believed to be dropping, (eg. for Nepal, Bajracharya 1983, FAO 1983a). The reasons for the slow down in yield improvements and even for yield decreases are due to a combination of factors. These include; the addition of marginal land to the world's cropland base, the loss of fertile land to urban and engineering developments, higher energy prices, a reduction in fallow in dry-land grain growing regions, a shortening of the fallow cycle in areas of shifting cultivation and the cumulative loss of top soil and fertility in major food producing regions. Brown (1978) reported that one fifth of the world's cropland was degrading at a rate which was intolerable in the long run. In the arid and semi-arid zones, 10% of the irrigated croplands are subject to waterlogging and 8% to salinization with considerable reductions in yields (UN 1977); the annual rate of desertification of cropland in tropical areas alone is believed to be 2.5 million ha (Burley 1984).

TABLE 1: Average cropland area capita<sup>-1</sup> under grain in 1950 and 1980 and predicted area capita<sup>-1</sup> in 2000; actual increase in cropped area between 1950 to 1980 and predicted increase 1980 to 2000 (from Brown 1978, Brown 1981).

	ha capita <sup>-1</sup>	% increase in cropped area
1950	0.24	26
1980	0.17	10
2000	0.13	

FAO (1980) suggested that the developing countries could double food production by the end of the century and meet increasing demand by improving production by 4% year<sup>-1</sup> during the 1980's, and 3.7% year<sup>-1</sup> during the 1990's. However, for this to happen the annual increases in yield ha<sup>-1</sup> would have to be considerably greater than those achieved between 1950 and 1970, a very unlikely development given the evidence presented above. Hence increased pressure on marginal lands, including encroachment onto more forest land, to provide food for a growing population is likely to lead to an increase in soil deterioration in cropping areas.

### Livestock Trends

The discussion is restricted to developing countries since in developed countries there have been difficulties in adjusting production to stagnating or shrinking domestic markets.

The growth in consumption of animal food products has exceeded that of production in the past two decades (FAO 1983 b). The less optimistic of two scenarios investigated up to the year 2000 (FAO 1981) suggested an 80% increase in animal production (cattle, sheep and goats) with an increase in livestock numbers of 15%. Yet, with few exceptions, any increase in animal production in the last 50 years in developing countries has been due to greater livestock numbers and not to improved productivity (ILCA 1981, Mahadevan 1982).

Livestock perform a number of essential functions in farming and cropping systems apart from direct food production (eg. draught power, dung production). FAO (1983b) suggested that if the value of draught power and utilized manure (estimated on the basis of the values of mechanical power and chemical fertilizers which can be replaced by livestock) are included, the total value of livestock production increases by almost 50% in developing countries. It can be argued however, that their value could be in fact even greater if one takes into account:

- a) Production foregone due to manure utilization for other purposes (eg. fuel)  
and
- b) Inability to utilize the full ploughing potential of livestock due to feed shortages resulting in weak stock (eg. Hoekstra 1984 for Kenya).

Draught power is at present inadequate (Mahadevan 1982), and the demand for animal power is expected to increase. FAO (1983b) has calculated that to enable food production in developing countries to double by the year 2000, power input to agriculture would have to increase by 2.3% year<sup>-1</sup>. If this involves only a 15% increase in the number of draught animals (see above), tractor numbers would have to increase by 400%. Since this is unlikely, a greater increase than 15% in the number of draught animals will be necessary as well as an improvement in their working performance in order for FAO's projections to be accomplished.

Small farmers sometimes derive a considerably greater proportion of their income from sales of livestock and livestock products than larger farmers within the same area and farming system, or derive more of their food from livestock than larger farmers (eg. for Nepal Conlin and Falk 1979, Gautam 1983). Livestock can provide food and income to the rural landless (Bernsten et al 1983). Hence it would seem to be important to maintain and develop fodder resources to which poorer sectors of society can have access.

The low productivity of livestock is due mainly to shortages of forage and of grazing areas and to the low quality of fodder; both of these have a seasonal dimension whereby, except in the wet tropics, livestock live on a sub-maintenance diet for considerable periods of the year (Crowder and Chheda 1982, Robinson 1985). To reverse this situation in order to improve productivity as suggested by FAO (1983b) would require substantial improvements in fodder availability and quality. However it has been suggested that all 3600 million ha of rangelands in arid and semi-arid lands are deteriorating (UN 1977). Further, there is no disagreement about the loss of grazing land to cropland (Mahadevan 1982, FAO 1983b, Sandford 1983). This is particularly significant since these areas are usually potentially the best grazing lands and particularly the best dry or cold season grazing lands. Hence increases in grazing areas or even their maintenance at present levels would be largely at the expense of further loss of forest or tree cover (much forest land is heavily grazed resulting in its gradual degradation).

In conclusion, it seems clear that crop, animal and wood products are likely to be in short supply in the future, at least on a regional and local basis. There are strong indications that the sectorial approach to likely supply and demand of natural resource products (livestock, agricultural crops and forestry) fails to appreciate the interrelated nature of these resource production systems. For instance, the expansion of cropland is at the expense of resources (forest,

grazing land) upon which its own production is dependent. It is hard to see how, as suggested independently by various studies (largely based on FAO data), expansion can occur in the use of land for any one of these production systems without consequent reduction in at least one another.

### SUSTAINABLE CROP PRODUCTION THROUGH AGROFORESTRY DEVELOPMENT?

It is within the context of the degradation of many land husbandry systems and of the increase in demand for products from frequently competing forms of land use (crops, livestock, forestry) that interest has grown in the capacity of agroforestry systems and technologies to reverse this trend. Agroforestry is a collective name for land use systems and practices where woody perennials (trees, shrubs, palms, bamboos etc) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components (Lundgren and Nair 1985).

One important objective of agroforestry is to obtain a more sustainable production from available resources. A key characteristic of such systems, which is often mentioned in agroforestry definitions, is that of the deliberate promotion of the woody perennial component (Anon 1982). Because agroforestry has considerable appeal, a large number of projects which include the introduction of agroforestry technologies have been initiated. However the belief that agroforestry technologies can increase production in a sustainable way is too often based on uncritical evaluation of the evidence.

#### Trees Within Cropland

Some of the potentially most attractive agroforestry systems are those in which the cropland fertility is improved or maintained by woody perennials growing within the cropland (as scattered trees or as closely planted hedgerows). Such systems rely on the fertility generating capacity of the cropland itself and therefore may avoid dependence on a shift of nutrients from land outside the cropland. Crop yields may be improved to such an extent that sustainability is achieved with crop production being maintained or even improved per unit area of "agroforestry combination" (rather than per unit area planted solely to the crop) thereby not requiring a larger area of agroforestry combination to produce the same quantity of crop. This is particularly important since land holding size is usually limited. The evidence which is often quoted to support the capacity of such technologies to solve soil fertility problems comes from areas ranging in climate from humid to semi-arid.

Torres (1983) hypothesized that maize production could be increased intercropped  $\text{ha}^{-1}$  on a sustainable basis through intercropping with a Leucaena leucocephala hedgerow which is managed to produce green manure. The hypothesis was based on available data on nutrient removal following the harvest of varying maize yields, and on the production of leaf prunings and foliar N from intensively managed Leucaena leucocephala hedgerows. The best response was expected to be in areas of low soil fertility and with closely spaced (1.5 m interrow spacing) Leucaena rows (i.e. greater production of Leucaena intercropped  $\text{ha}^{-1}$ ).

More recently, Kang et al (1985) have reported the results of a 6 year old alley cropping trial with Leucaena leucocephala (Cultivar K-28) in the humid area of South Western Nigeria. The Leucaena interrow spacing was 4 m and the plants were harvested at a height of 0.75 m five times a year. The mulch production of the plants from which successive prunings were not removed and onto which no N fertilizer was added produced a mean of 5.9 tonnes (dw) ha<sup>-1</sup> year<sup>-1</sup> and 173 kg N ha<sup>-1</sup> year<sup>-1</sup>. The maize grain yields could be sustained (over 5 years) at about 2.0 tonnes intercropped ha<sup>-1</sup> with Leucaena prunings. Without application of Leucaena prunings, maize yields dropped from 1.0 tonnes ha<sup>-1</sup> year<sup>-1</sup> to less than 0.3 tonnes ha<sup>-1</sup> year<sup>-1</sup> over 4 years. However all the plots in this trial (including the control) received some additional P, K and Zn.

Two farming systems in which trees have traditionally been grown scattered in the cropland are currently frequently being quoted as systems in which scattered trees sustain productivity of associated crops (through improvements in soil fertility): Acacia albida - peanut and millet associations in the Sahel (eg. Felker 1978, Nair 1984, Lundgren and Nair 1985, Young, this volume); Prosopis cineraria and pearl millet associations in the semi-arid and arid zones of India (Mann and Saxena 1980, Nair 1984, Lundgren and Nair 1985).

The case for the Acacia albida agroforestry system is convincing. Table 2 shows the quantities of dry leaf matter and N added year<sup>-1</sup> for fields with 10 to 40 trees ha<sup>-1</sup> (the range in density found on farmers' fields), and for the areas beneath the tree canopies alone or for the whole cropped area. The study showed substantially and significantly higher soil fertility status under tree canopies.

Summarising some data on these systems in Senegal, Poulain (undated) stated that average millet yields were 460 kg ha<sup>-1</sup> equivalent in the open between trees and 930 kg ha<sup>-1</sup> equivalent in the understorey of Acacia albida.

TABLE 2: Foliage (d.w.) and N added year<sup>-1</sup> by 10 and 40 Acacia albida trees ha<sup>-1</sup> of cropland; additions ha<sup>-1</sup> of understorey and total ha<sup>-1</sup> (derived from Charreau and Vidal 1965).

Trees ha <sup>-1</sup>	Leaf Litter (tonnes d.w.)		N	
	ha <sup>-1</sup> of tree understorey	total ha <sup>-1</sup>	ha <sup>-1</sup> of tree understorey	total ha <sup>-1</sup>
10	5.12	0.64	90.4	11.3
40	5.12	2.56	90.4	45.2

However there is still a question concerning the full reasons for differences in soil fertility under the trees. The experiments were conducted under well established trees on a research station. While Charreau and Vidal (1965) stated that livestock had been excluded from the research site for a number of years prior to the start of the study, it is known that dung concentrations can influence the fertility of sites for many years. This could be particularly relevant on those study sites which have deep soils. The residual effects of dung accumulation may be substantial at depths out of reach of annual crops but within the large volume of soil tapped by the deep acacia roots. Chareau and Nicou (1971) did state that the traditional management of this

agroforestry system involved fallow periods (both within the year and between years) when livestock return dung from areas outside the cropped area and distribute it in greater quantities under the trees where they seek shelter.

The situation with the Prosopis cineraria agroforestry system is far less clear. Foliar yield estimates range from 10 kg (d.w.) year<sup>-1</sup> (Paroda and Muthana 1981) to 72 kg (d.w.) year<sup>-1</sup> (Acharya 1980) for mature P.cineraria for the same area of Rajasthan. Yet actual measurements on trees in the DBH size range of 24-30 cm give annual foliar yields ranging from 3.3 kg (d.w.) (Bhimaya et al 1964) to 27 kg (d.w.) (Mann and Saxena 1983). Tree densities on private cropland vary from 20-40 trees ha<sup>-1</sup> (Mann and Saxena 1980) to 40 - 400 trees ha<sup>-1</sup> (Purohit 1981). Uncritical use of such figures could lead one to state that total annual foliar production of P. cineraria could be 66 kg (d.w.) ha<sup>-1</sup> (3.3 kg tree<sup>-1</sup> x 20 trees) or 28.8 tonnes (d.w.) ha<sup>-1</sup> (72 kg tree<sup>-1</sup> x 400 trees). The published information is insufficient to realistically evaluate the nutrient contribution of P.cineraria to cropland (Robinson in press). While a number of publications (Singh and Lal 1969, Saxena 1981, Shankararayan 1981) suggest that crop yields, and in particular those of pearl millet, are improved by P. cineraria, there appear to be no published research results to substantiate the statements (Robinson in press). Purohit and Khan (1980) quoted villagers' reasons for better crop growth under the trees as being due to fertility improvements by falling leaves, accumulation of bird droppings and dung concentration from cattle sheltering under the trees in summer, and to microclimate improvements. However this tree is usually lopped for fodder prior to leaf fall so leaf matter addition is not seen as a realistic explanation per se of the soil fertility and crop yield improvements which have been noted under the trees. Cattle and other livestock graze and browse extensively in areas outside cropland resulting in a shift of nutrients onto the croplands.

There is a shortage of critical information both on the quantitative contribution of trees to improved soil fertility and to increased crop yields which have in some situations been observed in the vicinity of trees. The mechanisms by which these improvements are achieved are also seldom understood. Soil fertility and crop yields can be improved when foliage is added to the soil as mulch, compost or via manure (from ingested material).

In order to select promising tree species for inclusion in trials to evaluate different species as soil fertility and crop yield improvers, data on the yield and nutrient composition of foliage of various species in different environments would be particularly valuable. However figures for foliar yields in non temperate areas are scarce.

A survey of worldwide literature on dry zone fodder trees (Robinson 1985, Robinson in press) showed that information on foliar yields is available for less than 20 species and for most of these there are difficulties in the interpretation of the data: eg. nature of leaves (freshweight of dry weight) not stated; size of tree or management history of the tree (such as canopy manipulation) not provided; sampling strategy not described.

It is possible that the maintenance or improvement of soil fertility and of crop yields on a sustained basis intercropped ha<sup>-1</sup> may be achieved by only a very few tree species in selected environments. Leucaena leucocephala is a species which can continue to produce large quantities of leaf material under frequent harvesting regimes. The range of other species which are known to be promising for similar purposes is still limited (eg. Gliricidia sepium, Cassia siamea). It is

more likely that the development of such managed systems of trees on cropland will help to reduce the dependence of crop production on the import of nutrients from forest and other non-cultivated land, or even on the import of artificial fertilizers.

### Agrosilvipastoral Systems

Agrosilvipastoral systems are management systems in which a mixed agricultural system (i.e. including both a livestock and a crop production component) is in some way integrated with, or dependent on tree or forest production. For the purpose of this review, at least some of the area under trees or forest in agrosilvipastoral systems is spatially distinct from the area under crops. A number of studies have attempted to quantify the contribution which livestock make to crop production (demand for draught power and for manure) and the contribution which nutrients from forestland and other non-cultivated land make to crop production. This substantial dependence on foliage from trees and grass for nutrients can be through its direct utilization as compost or ashes following burning, or indirectly as animal feed or animal bedding.

Table 3 provides data from a small area in Western Nepal (altitude 500 m to 2000 m; precipitation, 1000 mm to 2000 mm yr<sup>-1</sup>) on the ratio of land area under trees and grass (both government /communal and private) to cropland area, as well as the contribution which each area is estimated to make to the total calculated fodder demand for the livestock population of the area. Fonzen and Oberholzer (1984) suggested that the system is likely to break down because of the decline in soil fertility and crop production. The fodder supply is not sufficient to satisfy the demand (it does not add up to 100% of the estimated demand) and while there is some reliance on fodder from outside the area, animals are underfed during the dry season. It is interesting to note that the private land is nearly 7 times more productive in terms of fodder than land under government or common ownership. While a combination of both differences in inherent site conditions and in the management of the vegetation are likely to be responsible, the relative contribution of each factor to the differences in fodder production is unknown. The area from which these data were obtained is unusually well managed compared to the average farming community in the hills of Nepal.

TABLE 3: Ratio of land area under different uses and ownership categories and percentage of the estimated fodder demand supplied by each land category: Palpa District, Western Nepal (derived from Fonzen and Oberholzer 1984).

	Land Category		
	Cropland	Trees/Grass Private ownership	Trees/Grass Government/ communal owner
Area ratio	1	0.32	1.17
Fodder supply (% of demand)	10.5	51.5	27.5

Because of the difficulties in obtaining accurate average figures concerning a number of components of the farming systems of Western Nepal, only approximate figures could be given by Wyatt-Smith (1982) on the ratio of forest land required to sustain the fodder needs of the present farming systems. He suggested that his ratio of 2.8 ha of forest/shrub land ha<sup>-1</sup> of private agricultural land was conservative; indeed using other figures from his paper on average private holding size for the hills of Nepal, 7 ha of accessible unmanaged forest land are required ha<sup>-1</sup> of private agricultural land. Yet some of the areas which he mentions only have one ha of forest and grazing land ha<sup>-1</sup> of terraced agricultural land.

Using figures for Nepal as a whole, Panday (1982) suggested that the percentage of the fodder supply contributed by various components of the land production system is as follows: cropland 14%; grassland 27%; forest grass 15% forest trees 39%; private trees 5%.

The hilly area of Nepal covered by the Nepal-Australia Forestry Project has been better studied than other areas in terms of quantitative assessments of the complex linkages between the forest, the agricultural system and the human population. Yet, even for the same project area, estimates vary significantly. Shepherd (1985) calculated that the area of forest required to "sustain one ha of cultivated" land was 3.16 ha. The calculation assumed a proportion of annual foliage production which could be harvested for fodder and litter without impairing the future productivity of "fully productive" (protected), "average" (in species composition) forest; the assumptions concerning the demand for foliage were based on household surveys to determine the number of head loads obtained from the forest for various purposes (litter for manuring, animal bedding material, fodder) and the total fodder demand for livestock; conversion rates were used to convert head loads to oven dry biomass and various livestock types to standard livestock units. However not all the steps in the calculations were provided.

Byrne (1985), for the same area, calculated that 6.38 ha of forest land was required to sustain one ha of "agricultural" land. His calculations were based on the same harvestable amount of consumable foliage from the forest as used by Shepherd (1985) and on household surveys to determine the area under crops, the number of livestock, the fodder demand and the proportion of total fodder supplied by the forest (some conversion factors were not the same as those used by Shepherd). Again not all the steps in the calculations or all the conversion rates were provided.

The estimates of the amount of forest leaf material harvested for animal bedding and composting range from 24% to 44% of the total amount of foliage harvested from the forest (Byrne 1985, Shepherd and Griffin 1983, Shepherd 1985). It has generally been assumed that the same area of forest land which supplies fodder can also supply foliage for litter and bedding.

Byrne (1985) however estimated that, in his area of study, the present land use system consisted of only 1.1 ha of forest, scrub and grazing land for each ha of "agricultural" land.

Other statistics for Sindupalchock district (the district which is better endowed with forest out of the two districts of the project area) give ratios ranging from 1.54 ha of forest and grazing land for each ha of "agricultural" land

to 8.75 ha of "non-cultivated" land available for harvesting fodder and litter ha<sup>-1</sup> of "cultivated" land (Gilmour and Applegate 1985, Griffin et al 1985, Shepherd and Griffin 1983, Shepherd 1985).

It is not always explicitly stated what the various areas include: total areas of forest/scrubland grazing land for the district, or that which is accessible from the villages and therefore utilized; sometimes "cultivated" land is interchangeably used with "agricultural" land when a considerable proportion of "agricultural" land is in fact not "cultivated" (74% according to one estimate for Sindupalchok district, Shepherd 1985); the latter therefore contributes at least some nutrients to the land which is actually cultivated. Nevertheless all the publications agreed, even in the case of the highest estimate for the ratio of uncultivated to cultivated land, that the current supply of nutrients to the cultivated land is insufficient to maintain its productivity. The various estimates for the ratios have led to conclusions ranging from: i) the ratio is insufficient to sustain cultivated land even if the forest/grazing land was fully productive; to ii) the ratio of non-cultivated to cultivated land is sufficient provided that the former were reasonably productive (and it is stated that this condition is not met).

It has frequently been argued that the large population of largely "unproductive" livestock in the hills of Nepal should be reduced. Data provided by Karki (1984) suggests that, for a hilly area of Western Nepal, the manure production of the livestock population provides only 28% of the recommended fertilizer requirement of the cereal and vegetable crops of the area; further, some of this potential manure is lost during free range grazing away from cropland and during transhumance.

A similar pattern of heavy dependence of the crop production and farming systems on forest land emerges from the Kumaon mountain areas of India. Pandey and Singh (1984) calculated, on the basis of annual herb and leaf litter production from forest close to their study village, that 9.3 ha of forest land were required "to support one ha of the agricultural system" of the village. The analysis relied on energy values, derived from other sources, for the various inputs to and outputs from the system. Another study in the same region suggests that 18 ha of forest land are required to supply the fodder necessary to sustain each ha of "cultivated" land (Singh et al 1984) (assuming 10% of fodder needs being met by grasses on denuded slopes and 30% from the forest tree leaves). Yet the actual ratio was 1.33 to 1.0 and only 0.84 ha of good forest for each ha of "agricultural" land. Yet another study in the same region suggests an actual ratio of 1.58 ha of forest for each ha of "agricultural" land (Upreti et al 1985). In Kerala State (India), biomass from 40 ha of mixed forest is said to be required to sustain the productivity of each ha of Arecanut plantation (Chaturvedi, 1986).

## DISCUSSION AND CONCLUSIONS

It is quite likely that some of the assumptions behind the calculations of supply of fodder and litter from various land use categories and of the demand for these products are unrealistic. This would help explain at least part of the wide discrepancies found between various estimates of the area of uncultivated land required to sustain production from cultivated land and the actual ratios which are found in various areas. More studies are required to validate locally or even regionally some of the assumptions which have been derived in some cases from very different situations (eg. conversion rates for various inputs and outputs; fodder requirement of a livestock unit under village stall-fed conditions

or in free grazing situations; foliage production of forest harvested at different levels of intensity).

Some of the discrepancies are also clearly due to differences in definition of various land use categories (eg. agricultural land which includes only cultivated land or all private land including both cultivated and uncultivated land); and in the definition of various inputs and outputs (eg. fodder actually consumed by livestock or potential fodder consumption). The lack of clarity and precision in the presentation of data in many publications often precludes the drawing of realistic conclusions.

The efficiency of transfer of nutrients from non-cultivated land to cultivated land by livestock converting fodder to manure is also highly variable. The area of non-cultivated land required to sustain the productivity of cropland through conversion of fodder to manure will be considerably smaller where livestock are stall-fed than in areas where livestock spend most of the day or perhaps several months of the year grazing and browsing on non cultivated land.

Nevertheless, the weight of evidence, however imperfect, indicates that the crop-producing lands of the Himalayan region are degenerating because of insufficient nutrient inputs. (Bajracharya 1983, FAO 1983a, Karki 1984). The evidence also indicates that the pressure of foliar biomass and nutrient harvesting on non-cultivated lands is such that their productivity is also likely to be declining. Evidence from some other parts of the world suggests similar trends (Raintree, 1983 for Kenya; Robinson in press, for Western Rajasthan).

While the potential for improving soil fertility and crop production by introducing appropriate tree species within cropland is recognised, it is suggested that the main hope for reversing the present trend of overall decline in productivity in many environments in developing countries is to improve:

- i) the production of harvestable nutrients from non-cultivated lands (including forests);
- ii) the efficiency of transfer of nutrients from non-cultivated to cultivated lands;
- iii) the efficiency of utilization by the crops of the nutrients imported from non-cultivated land.

It is only possible to discuss briefly a few of the ways in which improvements of these three parameters can be achieved. Selected examples are used to illustrate some of the technical, managerial and policy factors which could have a significant impact on these parameters.

- i. The proportion of private land which is not cultivated is considerable in a number of farming systems. There is much scope for increasing the overall foliage production from such areas by planting selected species of trees at densities which still allow grass production. In many farming systems, farmers are prepared to protect trees on such land and to manage them for optimum production (eg. Fonzen and Oberholzer, 1984). However extension facilities for private seedling distribution are seldom sufficient to cover the areas where planting needs to be carried out. Farmers are not prepared to walk far to collect seedlings when the tree planting season usually coincides with the time of year when labour is at a

premium for other farm work. A considerable increase in and decentralisation of extension facilities is required in many countries. If private land is likely to be better managed than communal or government land, there may be advantages in the equitable privatisation of at least some such land. Any suggestion for such changes in the ownership of land is likely to face strong resistance from government forestry departments. The need for any privatisation to be equitable would be essential; small farmers often rely more on land other than their own for fodder and other foliage, compared to wealthier farmers.

On government and communal land, the choice of tree species must coincide with the requirements of local people and with their site requirements. In many cases, government institutions have chosen species (eg. pines and eucalypts for timber, paper and fuelwood) which are not the most appropriate to satisfy the various products required by the community. Preferences for forest products often differ between men and women and between wealthier and poorer sectors of the same communities. The question has to be faced as to how much forest land has to be kept for fodder and other foliage production. Is foliage production compatible with the management of forest for other products, even if their management is separated over time, or should different areas of forest be managed separately for various products, perhaps aimed at different users? In many areas, for instance in the Himalayan region, the most important forest product is foliage.

The criteria for the selection of species aimed at foliage production on both private and government or communal land should take a number of factors into account. In all cases foliar yields and nutrient content of the leaves are important; species which have the ability to effectively add nutrients to the system (eg. by fixing nitrogen, facilitating the availability of nutrients from soil sources where they are otherwise unavailable), rather than purely recycle nutrients returned to the soil following decomposition, are also advantageous. In situations where trees are to be lopped, time in leaf in relation to foliage demand, and resilience to harvesting are important, as is foliage digestibility in the case of fodder foliage.

There are different ways of managing trees for foliage production. Oak forest in the Himalayan region is usually managed by frequent stem pruning of the tall trees. However it is possible that the pollarding of denser stands of trees which are kept smaller may provide more foliage per unit area of forest. Further, the labour requirement necessary to harvest a unit amount of foliage would be reduced, thereby enabling a larger area of forest to be harvested for the same labour input. Such a system could spread the harvesting pressure and reduce the trend of "peripheral degradation" (degeneration at the margin) of the forest described by Moench and Bandyopadhyay (1986) and which occurs in most of the Himalayan region; foliage production could therefore be increased. The easier harvesting of smaller trees could be carried out by children (tall trees are generally lopped by adults, and particularly by women, eg. Fox 1983, Singh et al 1984) thereby reducing the labour requirement of adult women which could itself result in improved management in other sectors of the farming system. A greater sustainable foliage production per unit area would release land for more conventional forms of forest production.

- ii. The main way in which the efficiency of nutrient transfer from forest to crop land can be achieved, where foliage is fed to livestock, is by increasing the proportion of stall-fed animals; this would increase the amount of dung available for application to cropland from each unit area of fodder harvested from trees and forest land. While dung can be collected from land which is freely grazed by livestock, the labour requirement for this activity is high. The nutrient loss should also be lower from dung (and urine) accumulated with leaf litter in a stall fed situation compared to dung left lying in grazing land. Again there are a number of technical and socio-economic factors impinging on uncultivated land management, which determine the extent to which a change from free range grazing to stall-feeding is feasible. Some of these, including those of labour in foliage harvesting, are discussed above. Fox (1983) has argued that substituting stall-feeding for grazing might be more difficult than is generally believed. This is because fodder collecting (in his study area) requires the labour of healthy adult women which is already the most overworked labour sector, whereas grazing makes use of the labour of children and the elderly. The extent to which children attend school is also likely to affect the feasibility or desirability of stall feeding.

Technical factors concerned with compost and dung management also influence the efficiency of the transfer of nutrients to cultivated land. Rural communities manage compost and dung in different ways, and some practices are more conservative of nutrients than others. Research should identify the most appropriate means of reducing nutrient loss in different climatic areas and given local cropping patterns.

- iii. In different cropping systems, the timing of the demand by crops for nutrients varies. The release of nutrients from applied dung and compost/mulch should be matched with the crops' demands. Nutrient release rates vary with temperature (altitude and latitude) and rainfall regime. Mulch made of small leaves (eg. Leucaena leucocephala) may decompose too fast in some situations (eg. Philippines) and the nutrients may be leached out of the rooting zone of crops before the crop has been able to take up the nutrients. Larger leaves, with slower decomposition rates, would be more appropriate in such cases. Conversely, at higher altitudes or in low rainfall areas, faster decomposing mulch or compost may be desirable.

In many parts of the world, crop production is dependent on the shift of nutrients from forest and other non-cultivated land to cropland. The shrinking forest areas and competing demands on forests for different products make it imperative that their production potential be improved. While trees located within cropland can improve the nutrient status of cropland soils, the indications are that the main source of nutrients for maintaining cropland fertility originates and will continue to originate from forest land and other non-cultivated lands. It is necessary that forest departments take into account the dependence of farming systems on foliage harvesting from forest land in their overall forest policy and in their management prescriptions. Research can help identify ways in which tree and forest production can be increased and made more appropriate to the need of nutrient exports. The proportion of research funds for renewable natural resources which is allocated by central governments and international organizations to forestry should reflect this dependence of agricultural production on forestry. A number of changes in attitudes to the management of government and communal level, both at community and at

government level, are necessary to optimise the production of agricultural and forest products.

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## 2. THE POTENTIAL OF AGROFORESTRY AS A PRACTICAL MEANS OF SUSTAINING SOIL FERTILITY\*

Anthony Young

International Council for Research in Agroforestry,  
Box, 3067, Nairobi, Kenya

### SUMMARY

The maintenance of fertility through soil biological processes requires management practices which control the quantity, quality and timing of decomposition of plant residues. Agroforestry is one of the major practical management methods which has the potential to bring this about. It is widely applicable, through many different kinds of practice, has substantial effects on the soil, and is relatively free from supply constraints. Trees restore soil fertility through their potential to increase the supply of organic materials and nutrients, to reduce nutrient losses and to control the quality and timing of inputs. A first approximation to a plant/soil organic matter cycle under agroforestry is presented, showing that if the assumptions on which it is based can be verified, agroforestry has the potential for the design of land use systems that combine production of annual crops with maintenance of soil fertility. The significance of work on different fractions of organic matter, and on root residues, is discussed; these studies suggest benefits from mixtures of woody and herbaceous litter. Results of work on soil rest period (fallow) requirements are summarized; it has yet to be shown whether spatially based agroforestry systems can be more efficient, in terms of land requirements, than crop/fallow rotations. Current research in agroforestry suffers from over-emphasis on pragmatic approach at the expense of an understanding of basic processes. Research is needed on the decomposition of woody and herbaceous residues, singly and in combination, and their effects on soil properties.

\* This is a shortened version of a publication which first appeared as ICRAF Working Paper 34, Nairobi. 1985, 28 pp

### INTRODUCTION AND OBJECTIVES

The Tropical Soil Biological and Fertility Programme (TSBF) is a collaborative programme of research, the objective of which is "to determine" the management options for improving tropical soil fertility through soil biological processes" (Swift, 1984). This objective can be achieved through two stages:

- i to develop a predictive understanding of the functioning of biological processes in tropical soils, and their role in contributing to fertility;
- ii to apply such an understanding to the development of practical management measures to sustain and improve fertility.

The present account originated from two papers presented to meetings of the TSBF (see Acknowledgements). This coincided with and ICRAF review of the role of agroforestry in soil conservation, taken in its broader sense to mean conservation of fertility as well as prevention of erosion. An account of soil

productivity and management under agroforestry systems have been given by Nair (1984).

The objectives of the present paper are:

- i To outline some of the hypotheses of the TSBF that are of particular significance to agroforestry.
- ii To show the potential of agroforestry as one of the major practical management alternatives for maintenance of tropical soil fertility through biological processes.
- iii Based on present knowledge of plant/soil organic matter processes, to give a preliminary outline of a possible organic matter cycle under agroforestry.
- iv To discuss the significance for agroforestry of recent advances in knowledge of soil organic matter processes.
- v To outline needs for research.

It should be emphasized that this is an interim statement of work in progress, and still at a relatively early stage. Much of it consists of hypotheses not yet fully supported by experimental evidence; these hypotheses, however, have substantial and favourable consequences if they can be verified.

Lastly, it should be emphasized that as a working paper, this is intended as a means to invite criticism and comment on the ideas presented.

### **BIOLOGICAL PROCESSES AND SOIL FERTILITY**

Fertility is the capacity to support plant growth, and as such arises jointly from climate and soil. However, it is frequently desirable to isolate the element of soil fertility, which can be taken as the capacity of the soil to support plant growth, given satisfactory climatic and other environmental conditions.

The main soil conditions contributing to fertility are favourable physical properties, an adequate supply of nutrients, and absence of toxicities. None of these conditions are biological. The indifference of plant growth to soil organic matter as such is shown by the high crop yields that can be obtained, with fertilizer, on sandy soils with well under one percent organic matter, and by the not especially high fertility of peats.

It is widely recognised, however, that soil organic matter greatly influences fertility, through its effects on both physical conditions and nutrients supply (see, e.g. Young, 1976, p. 300; Swift and Sanchez, 1984, p. 7). Formerly, the emphasis was simply on maintaining the quantity of organic matter. This remains the priority, since if the soil humus can be kept above some critical level, which varies with environment, then most other favourable consequences will follow. Recent work, brought into focus by TSBF, has drawn attention to two other aspects: the quality of organic matter and the timing of its decomposition.

'Quality' is a loosely-defined term which refers to various aspects of physical and chemical composition. The term may be applied to both plant residues (litter

and roots) and to soil humus. In the case of plant residues, it refers primarily to the relative proportions of sugars, nutrient elements, lignin and other polyphenols (Swift et al., 1978). This aspect is discussed further below.

The timing of mineralization of soil organic matter controls the release of nutrients; and since nutrients are also subject to leaching, fixation and other losses, it is advantageous if this release can be effected at the same time as the major requirements for uptake by plant roots. The main control over timing of release is the period when plant residues are applied to the soil; other controls are the quality of such residues, how they are applied (e.g. to the surface or buried), physical and chemical soil properties, especially moisture, and the soil fauna.

There are two basic hypotheses underlying the TSBF, concerning synchrony in nutrient release and uptake, and soil organic matter, the SYNCH and SOM hypotheses respectively.

The SYNCH hypothesis is that the release of nutrients from plants, and their subsequent transformation via litter, humus and mineralisation, can be synchronised with plant growth requirements, by means of management measures.

The SOM hypothesis is that the amounts and types of soil organic matter, and thus its effects on soil properties and fertility, can be regulated by the types of litter and root residues.

Thus, seeking to improve soil fertility through biological means, the factors that it is possible to manipulate are:

- i the quantity of plant residues;
- ii the types of residues, and thus their quality;
- iii the timing and manner of their addition;
- iv the soil conditions that affect their decomposition.

### **PRACTICAL MANAGEMENT OPTIONS**

These soil changes have to be brought about through practical management options, measures that the farmer with limited capital and technical resources can carry out on a field scale (as distinct from horticultural). In the first report of the TSBF programme there is a list of 21 soil biological processes or effects, with management practices by which they can be manipulated. Table 1 is a transformation of that list, in which the management practices are given in the first column, followed by their soil biological effects. Thus, fertilization (inclusive of liming and sulphur addition) can affect root turnover, rate of organic matter decomposition, solubilization of rock phosphate and denitrification.

Two columns have been added, "non-biological reasons" and "supply constraints". The former refers to practices that are usually carried out with objectives in mind that are not primarily control of soil biology. Thus fertilizers are added to increase the nutrient supply directly, crop rotation to achieve balance in the nutrient demands, intercropping for a variety of reasons, ecological and economic. This applies also to management of burning, drainage, application of pesticides, and grazing control. All these practices have soil biological effects, but these are not the main reasons why they are carried out.

Thus, pesticides are applied to kill insects; the fact that they may also reduce the detritivore population is a side effect.

This situation also applied to agroforestry practices. The most common reason for them is probably to obtain firewood from the farm. Others are to produce fodder for livestock, fruit (for food or cash sale), or for food conservation. In other cases, agroforestry is practised with the perceived objective of soil fertility improvement. Examples are the practice of laying Erythrina poeppigiana prunings on the soil in coffee cultivation, found widely in Central and South America, and the use of Leucaena leucocephala as a managed rotation in parts of the Philippines.

The fourth column in Table 1, supply constraints, indicates where the application of a management practice is often prevented or restricted by problems of supply. This is obviously so in the case of fertilizers. For grass mulching, composting or application of farmyard manure, there is frequently not the quantity of material available for application to the main area of field crops. From the 1950s onwards it was shown that 5-10 t/ha per year of manure is very beneficial to the soil; but in most farming systems, the supply is not likely to exceed 1-2 t/ha per year, and this alone does not maintain soil organic matter level. In herbaceous legume fallows the constraint is one of land; green manuring, solely for the purpose of ploughing in the residues, is not viable. With regard to incorporation of crop residues, nothing so well combines practicability, even at a low level of technology, with clear beneficial effects on the soil; but the poorer farmers frequently have more pressing uses for crop residues, as livestock feed (especially in the Indian subcontinent) or construction materials for compounds (e.g. northern Nigeria). The possible supply constraint to tillage management is in the supply of herbicides where required for minimum tillage.

Summarizing this position, the practical management measures that are listed can be put into the following groups:

- i Practices carried out primarily for reasons other than their effects on soil biology: fertilization, crop rotation and intercropping, management of burning, drainage, pesticides and grazing.
- ii Practices in which soil biological effects are a substantial and perceived purpose, but which for poorer farmers are often subject to supply constraints: green manuring, mulching, composting and manuring, incorporation of crop residues, and tillage management.
- iii Direct biological manipulation; the case listed in the table is mycorrhizal inoculation but there are others, e.g. fumigation to destroy nematodes.
- iv Agroforestry, which: (a) can be practised for economic reasons, with side-effects on soil biology and fertility, or with such effects as a perceived benefit; and (b) is often practicable for the poorer farmer, or can be made so by a modest level of governmental assistance (e.g. tree nurseries).

TABLE 1: Management Practices which influence soil biology and fertility. Derived from Swift (1984, Table 1).

Management practice	Soil biological effects, see below	Non-biological reasons	Supply constraints
Fertilization, liming	1, 10, 12, 14	x	
Crop rotation, intercropping	2, 21	x	
Legume fallow (herbaceous)	3		
Mulching, compost, manure	7, 8, 19		
Crop residue management	7, 8, 15, 17		(x)
Tillage management	6, 20		(x)
Agroforestry practices	2, 3, 4, 7, 15, 19	(x)	
Control of burning	11	x	
Drainage	13	x	
Pesticide management	5, 9, 20	x	
Grazing control	18	x	
Mycorrhizal inoculation	16		

x Normally or frequently (x) Sometimes

Soil biological effects:

1. Increase root production
2. Cause variation in root exudates
3. Cause N fixation
4. Cause upward movement of nutrients
5. Reduce detritivore populations
6. Increase biological oxidation
7. Low quality residues promote synthesis of organic colloids
8. Low quality residues lead to nutrient immobilization
9. Insecticides increase microbial immobilization
10. Liming increases rate of soil organic matter decomposition
11. Burning increases mobilization
12. Addition of S increases solubilization of rock P
13. Drainage increases nitrification
14. Nitrate fertilization increases denitrification
15. Nutrient-rich residues increase reduction of S, F, Mn
16. Mycorrhizal inoculation increases nutrient uptake
17. Crop residues increase soil particle aggregation
18. Heavy grazing increases soil surface capping
19. Organic residues maintain macrofauna and thus soil pores
20. Termites reverse clay illuviation, tillage or pesticides destroy termites
21. Crop rotation reduces toxification of soil

In summary, there are three management practices which are practicable, applicable in a wide variety of circumstances, and which have substantial effects on soil biological properties:

- crop residue management
- tillage management
- agroforestry

The first two of these are linked in techniques of minimum tillage. There are also possibilities of combining (herbaceous) crop residue management and/or tillage management with agroforestry.

There is a wide range of agroforestry practices, and many thousands of local agroforestry systems. Some are traditional indigenous land use systems, other more recently developed. A list of the main practices is given in Table 2.

TABLE 2: Agroforestry practices. (Adapted from the ICRAF agroforestry systems inventory)

Improved shifting cultivation

Planted tree fallow

Taungya

Alley cropping

Boundary planting

Live fences

- mainly barrier function
- multipurpose

Multipurpose trees on:

- cropland
- rangeland or improved pastures

Woodlots (with multipurpose management)

Protein banks

Trees as shelter for:

- crops (windbreaks, shelterbelts)
- animals
- homesteads

Trees for soil conservation:

- on bunds, terraces
- strips
- hedges

Trees in water management

Home gardens

Plantation crop combinations:

- with lower-storey tree/shrub crops
- with herbaceous crops
- with upper storey trees (shade of multipurpose)
- with pastures and livestock

Livestock under trees

Dune fixation

Aquaforestry (including mangrove)

Apiculture with forestry

## **THE BASIS OF PLANT/SOIL INTERACTIONS UNDER AGROFORESTRY**

The foundation for assuming that agroforestry systems can lead to a steady state of the soil lies in the observation that tree fallows build up soil fertility, as demonstrated by systems of shifting cultivation. This counteracts the decline in fertility under continuous cultivation of annual crops.

There are three agroforestry practices based on a time rotation of trees with crops: improved forms of shifting cultivation, planted tree fallows, and taungya. Improved shifting cultivation started with the corridor system developed at Yangambi on the former Belgian Congo; there are versions, including a livestock component, more recently devised for the Amazon (Bishop, 1982). In planted tree fallows, a fast-growing, nitrogen-fixing tree is planted in blocks, rotated around the agricultural land; the larger woody parts may be harvested for firewood, the remainder is returned to the soil. In taungya systems, the major objective is the harvest of the tree, annual crops being interplanted for 1 - 3 years; this is successfully practised in forest villages of Thailand and the shamba systems of Kenya, less effectively in some other instances.

More flexibility in design comes from substituting spatial arrangements of trees and herbaceous plants for rotations in time. The trees may be spaced more or less randomly, as in home gardens and some types of sylvopastoralism; regularly, in grazing beneath coconuts, rubber or timber trees; in single rows, as in boundary planting and some forms of alley cropping; or in strips several trees wide, also possible in alley cropping designs. In practices dependent upon spatial arrangements, a large range of interactions come into existence at the tree/crop interface. Important as these are, they will not be considered in the present discussions (cf. Huxley, 1983).

Essentially, therefore, an agroforestry system is made up of trees and herbaceous plants, each occupying a certain proportion of space and/or time. One way of looking at this situation is as a continuum between 100% crops and 100% trees, the former degrading the soil, the latter restoring fertility, but with the crops normally giving the higher economic return. Agroforestry systems lie somewhere between these extremes, and seek to find a mixture of components that will combine sustainability with an acceptable economic return. Such three-dimensional models are outlined by Huxley (1984, 1985). Soil-related aspects of a range of different agroforestry practices have been outlined by Nair (1984).

The basis for the role of agroforestry in sustainable land use systems is the same, whether there is a rotation of components in time or an arrangement in space: namely, that a net loss of soil fertility under the cropping component is balanced by a net gain under the tree component. Trees achieve favourable effects on the soil through range of processes, listed in "Effects of trees on soils", Chapter II.

## **THE PLANT/SOIL ORGANIC MATTER CYCLE**

### **Conceptual basis and the cycle under vegetation and cropping**

The starting point for discussion of organic matter cycling is the model of the carbon balance under shifting cultivation constructed by Nye and Greenland (1960). There are two components to this model: the stores and flows of organic

carbon under natural fallows (forest or savanna), and the basic assumption of a decomposition constant in the oxidation loss of soil organic carbon.

Although there has been much subsequent quantitative work on organic matter cycling under natural vegetation, the orders of magnitude for stores and flows of carbon established by Nye and Greenland have proved to be correct. Table 3 gives representative values for these stores and flows for three climatic environments: lowland rain forest, moist savannas (annual rainfall 900-1200 mm) and dry savannas (annual rainfall 600-900 mm). The savanna data are subdivided according to whether it is burnt (with assumed loss of above-ground vegetation) or unburnt).

The losses of carbon from the soil humus, through bacterial oxidation, are based on the concept of a decomposition constant. That is the amount of carbon lost in unit time through oxidation is assumed to be proportional to the amount of carbon initially present. This proportion is the decomposition constant, usually expressed as a percentage. The rationale for this assumption is that the oxidizing activity is proportional to the soil fauna present, the population of which is dependent on the substrate which supports it. In this paper, the decomposition constant under forest,  $k_f$ , is taken as 3% (0.03) and the decomposition constant under cultivation,  $k_c$ , as 4%. The assumption of a decomposition constant provides a homeostatic mechanism whereby soil organic matter will tend towards an equilibrium value under constant inputs, however large or small these may be.

This model takes no account of the existence of varying qualities of soil organic matter, with differing rates of breakdown, the implications of which are discussed later.

Figure 1 gives the models for the rainforest and moist savanna conditions, showing the position under equilibrium conditions. Gains to soil humus equal losses, at  $190 \text{ g/m}^2$  per year in the forest environment and  $120 \text{ g/m}^2$  per year under savanna. The soil humus contents of 6330 and  $5700 \text{ g/m}^2$  carbon respectively are equivalent (making a number of assumptions) to topsoil organic matter levels of 4.24 under forest and 3.8% under savanna.

As a basis for discussing carbon flows under agriculture, one of these environments only is selected, that of rainforest. A cereal crop is assumed (typically maize), with two levels of grain yield: 1000 kg/ha, typical of low-input or 'traditional' agriculture in developing countries; and 3000 kg/ha representative of intermediate inputs, i.e. improved farming, with some use of fertilizers, but lower than in high-capital high-technology agriculture. For each yield level, two alternatives considered are that the crop residues are or are not returned to the soil.

Figure 1  
The carbon cycle under natural vegetation. Cf Table 3. Source: Young (1976, p111), based mainly on data in Nye and Greenland (1960).

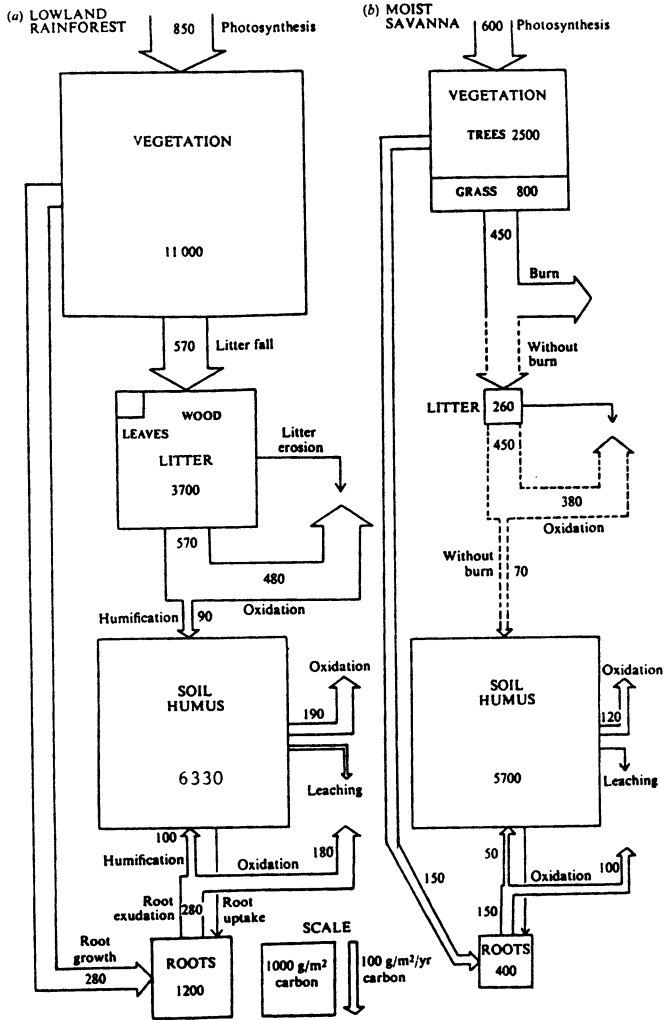


TABLE 3: Estimates of typical values of parameters in the carbon cycle under natural vegetation. Based on data in Nye and Greenland (1960), with some modifications. All values refer to organic carbon, which is assumed by Nye and Greenland to constitute approximately half of organic matter.

<i>A. Stores of carbon (Values in g/m<sup>2</sup>)</i>						
	Lowland rainforest	Moist savannas	Dry savannas			
Living vegetation: trees	11000	2500	2400			
grasses	0	800	400			
roots	1200	400	200			
Dead vegetation: leaf litter	100	60	30			
wood	3600	200	200			
Total living vegetation	12200	3700	2800			
Total dead vegetation	3700	260	230			
Soil humus	6330	5700	1700			
Total in plant-soil system	22230	9660	4730			

<i>B. flows of carbon (Values in g/m<sup>2</sup>/yr)</i>						
	Lowland rainforest	Moist savannas		Dry savannas		
		Unburnt	Burnt	Unburnt	Burnt	
Net intake from atmosphere	850	600		170		
Loss in burning	0	0	450	0	120	120
Root growth	280	150		50		
Litter and timber fall	570	450	0	120	0	
Humification of litter	90	70	0	20	0	
Oxidation loss in above	480	380	0	100	0	
Root exudation	280		150		50	
Humification of roots	100		50		20	
Oxidation loss in above	180		100		30	
Total additions to soil humus	190	120	50	40	20	

Table 4 gives stores and flows of carbon for four conditions: low and moderate yields, each with removal or retention of residues. It is assumed that cultivation has already lowered soil humus to half of its level under forest, 3500 g/m<sup>2</sup> carbon. The harvest index (grain as percent of above ground biomass) is taken as 33%, and biomass of roots as 33% of the above-ground biomass. The same assumptions are made as in Table 3, namely that the split between humification and oxidation loss is 15% : 85% for crop residues (litter in Table 3), and 33% : 67% for roots.

There is net loss of carbon from soil humus under all four sets of assumptions. Its level is lowered annually by about 1% of its initial level under the most favourable conditions and 3% under the least favourable. If such cropping were continued (avoiding erosion), the soil humus would reach equilibrium at levels shown in Part C of the table. On grounds of soil structure maintenance, erosion resistance, and retaining a nutrient source and retention medium, these levels are certainly unacceptably low for the first three cases, and even in the most favourable case represent only one third of the level under natural forest.

The situation for moderate yields with residues removed is shown diagrammatically in Figure 2. As compared with the model under forest (figure 1) the feature is the high proportion of total carbon in plant-soil system that is contained in the soil store. Losses are shown by shaded boxes, the dotted area for 5 years of cereal cultivation with removal of residues.

### **The soil organic matter balance under agroforestry**

If assumptions made in the preceding section are justifiable, it is possible to construct a first approximation of cycling of organic matter (represented by carbon) under a schematic agroforestry system. It should be re-stated that this simplified model takes no account of the existence of fractions of organic matter with differing rates of decomposition.

The model is based on the following assumptions:

- A humid tropical (rain forest) environment;
- The planting of trees which have a rate of growth, and thus litter production, equal to that of a natural forest fallow.
- An agroforestry practice in which trees and crops each occupy 50% of land in space or time.
- The assumptions, from Table 4, of a 'moderate' crop yield (3000 kg/ha grain) with crop residues removed.
- The assumptions on processes set out in the above section.

The effects are virtually the same for a rotation of trees and crops as for a spatial mixture of equal proportions, except for a toothed pattern to the curve of soil carbon with time in the former case compared with a smooth curve in the latter.

The assumptions are perhaps unduly favourable (for soil organic matter) in that only one cereal crop per year is taken, whereas two crops are common in humid tropics; but errs on the cautious side in assuming that the trees planted in the agroforestry system have only the same rate of growth as natural vegetation.

In Figure 3, the upper diagram shows what happens when the forest is first cleared. Under forest conditions, inputs and outputs of soil carbon are equal, at  $190 \text{ g/m}^2$  per year. Under the crop they are very unequal, leading to a rapid fall in soil humus level. The half-and-half agroforestry system still leads to a combined loss of  $100 \text{ g/m}^2$  carbon per year.

The lower diagram shows the situation when soil carbon has reached  $3450 \text{ g/m}^2$ . Inputs from tree and crop components are unchanged, but the assumption of the decomposition constant leads to approximate halving of the oxidation losses. Under the crop alone there is still a net annual loss of  $86 \text{ g/m}^2$  carbon, but this is balanced by an equal net gain under the tree component. The agroforestry system as a whole — soil, soil organisms, tree, crop and environment — is stable. This equilibrium is reached with soil organic matter at slightly over half its natural level, a proportion generally taken to be acceptable in agriculture.

This result is exciting in the prospects which it opens up. It amounts to an hypothesis that, provided the assumptions can be verified, agroforestry systems can be designed that are productive in terms of crops, and at the same time lead to a steady state of soil organic matter. The features that require verification are that the processes operate in the manner stated, and that the general magnitudes of plant growth assumed are correct.

This result is currently being followed up, through the construction of models of the cycling both of organic matter and nutrients, the former taking into account the different organic matter fractions. There is a substantial body of source data, both studies of cycles as a whole and individual components (eg. litter fall, nitrogen fixation). This exists for:

- natural vegetation; there is an imbalance towards studies of forest, but with some data on savanna and semi-arid ecosystems.
- agricultural systems;
- forest plantations; these studies arise from the concern of foresters about the long-term effects on soils of fast-growing forest plantations;
- agroforestry systems; there are a substantial number of records of individual components, particularly tree growth rates and litter production, and a few studies of total cycles.

Computerized models are being developed, of greater complexity but with similar basis to those of Figures 1-3.

TABLE 4: Estimates of the carbon cycle under cereal crops of low yields (1000 kg/ha) and moderate yield (3000 hg/ha). Values in g/m<sup>2</sup> carbon.

Crop Residues:	Low yield		Moderate yield	
	Removed	Retained	Removed	Retained
<u>A. Stores</u>				
Crop:grain	50	50	150	150
vegetative	100	100	300	300
roots	50	50	150	150
Soil humus (OM = 2.33%)	3500	3500	3500	3500
Plant soil system	3700	3700	4100	4100
<u>B. Flows</u>				
From atmosphere	200	200	600	600
Root growth	50	50	150	150
Harvest	50	50	150	150
Crop residues, removed	100	0	300	0
" " retained	0	100	0	300
Humification of residues	0	15	0	45
Oxidation loss in above	0	85	0	255
Root exudation	50	50	150	150
Humification of roots	17	17	52	52
Oxidation loss in above	33	33	98	98
Total additions to soil humus	17	32	52	97
Loss from soil humus ( $k_c=4\%$ )	140	140	140	140
Net changed in soil humus	-123	-108	-88	-43
<u>C. Equilibrium level of soil humus</u>				
Carbon, g m <sup>-2</sup>	425	800	1300	2425
Equivalent topsoil OM%	0.28	0.53	0.87	1.62

Figure 2

The carbon cycle under a moderate-yielding cereal crop in the lowland rainforest zone. Shaded areas show net losses of soil humus as follows: 1 yr ret. = loss in 1 year, crop residues retained; 1 yr rem. = loss in 1 year, crop residues removed; 5 yr rem. = loss in 5 years, crop residues removed.

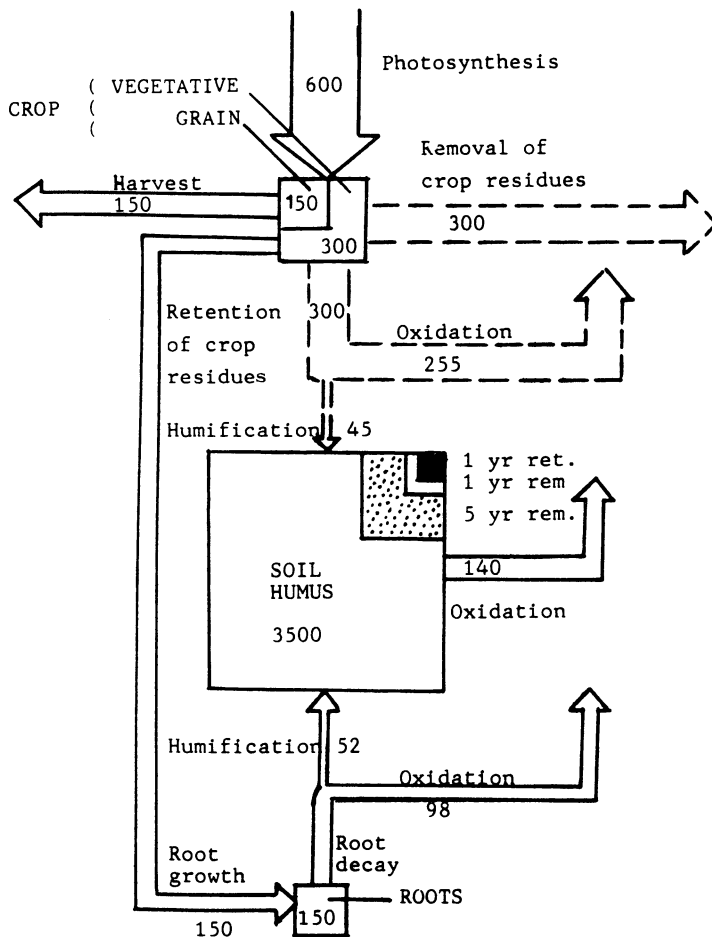
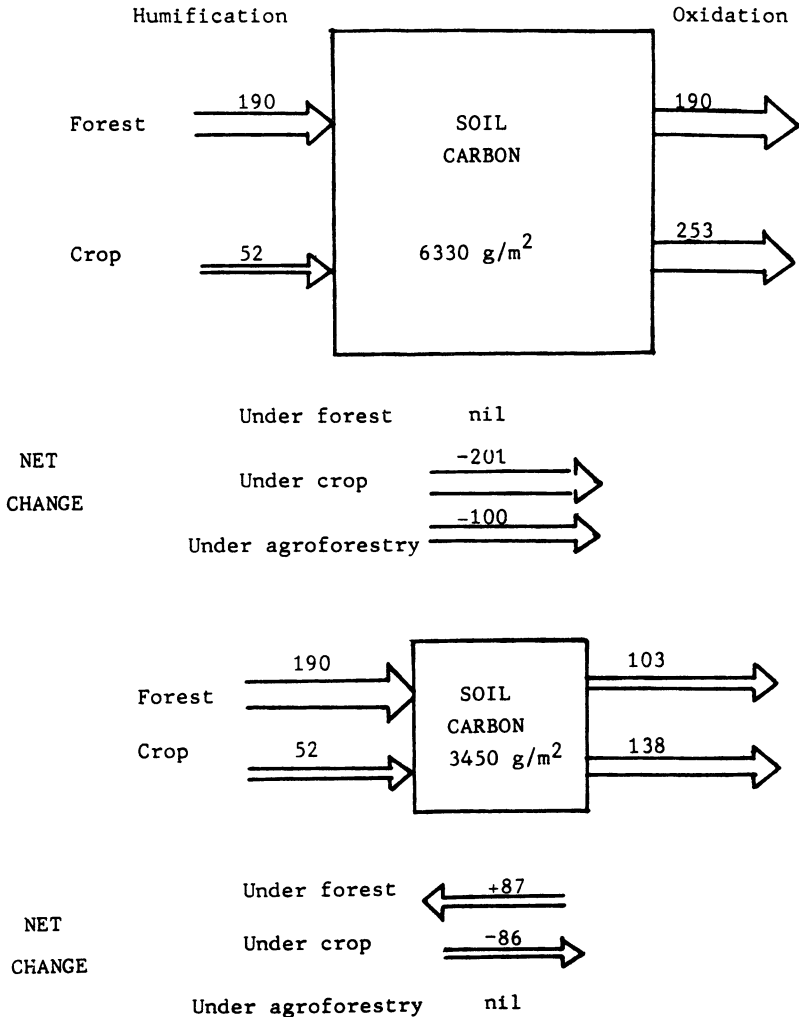


Figure 3  
 Changes in soil carbon,  $\text{g/m}^2$ , under forest, a cereal crop and agroforestry, at two levels of soil humus carbon. Assumptions are: (i) cereal crop, moderate yield, residues removed; (ii) decomposition constants, for forest,  $k_f = 3\%$ , for cultivation,  $k_c = 4\%$ .



## SPECIFIC ASPECTS OF SOIL ORGANIC MATTER

Two advances in knowledge about soil organic matter are of much potential significance to agroforestry. These are the distinction between fractions with differing rates of loss, and the role of root exudation and decay.

### Fractions of organic matter

The former assumption (employed in the above model) was of a single decomposition constant for soil organic matter, a fixed proportion of the current store that was lost by bacterial oxidation each year. Reasoning from observed equilibrium levels led to the supposition of constants of some 3% under natural vegetation, rising to 4% under agriculture. It was soon suspected that the losses during the initial decomposition of plant residues, for the first six months to a year, were very much faster (Young, 1979 pp. 114-5). The position has been transformed by carbon isotope studies, which enable the progress of labelled plant material to be followed through the system (Jenkinson, 1971, 1977; Jenkinson and Ayanaba, 1977; Sauerbeck and Gonzalez, 1977; Paul and van Veen, 1978; Gonzalez and Sauerbeck, 1982).

The addition of carbon-14 labelled residues to a soil enables the loss of this specific material to be followed over time. Studies both in temperate and tropical soils have a decay curve of the same form; a very rapid loss over the first 3-6 months, changing fairly abruptly into a slower rate of exponential decay. For studies in the UK and Nigeria, using the same plant material, the two curves could be superimposed almost exactly if the time scale for Nigeria was divided by four. This led to the assumption that these correspond to two different fractions of organic matter.

The fast-decay fraction is lost rapidly, such that in tropical soils, some 65% of the labelled plant material is lost within the first 6 months or less. It seems likely that this corresponds to the loss in 'conversion' from litter to humus in the Nye Greenland model, which takes values of 75-90% loss for above-ground litter and 50-80% for roots.

The next organic matter fraction is lost in an exponential decay manner, with a half-life of between 3 and 6 years. These are the only two fractions directly monitored by carbon-14 labelling.

The equation underlying the Nye-Greenland model is of the form:

$$C_1 = C_0 - kC_0$$

or

$$C_1 = C_0 (1-k)$$

where  $C_0$  = initial carbon,  $C_1$  = carbon after 1 year, and  $k$  is the decomposition constant expressed as a fraction.

This simplified equation takes no account of the effect of decrease in the course of the year on the quantity of carbon remaining. For short periods of time, the relation is more precisely expressed by an equation of exponential form:

$$C_t = C_0 \cdot e^{-rt}$$

where  $C_t$  = carbon after time  $t$  (years),  $e$  is the exponential constant, and  $r$  is a parameter. For slow rates of decay ( $k$  and  $r < 0.1$ ) the equations are nearly equivalent and  $r \approx k$ . For a single organic matter fraction the half-life  $T_{1/2}$  is given by:

$$T_{1/2} = \ln(2)/r$$

With two fractions, the equation becomes:

$$C_t = C_1 \cdot e^{-r_1 t} + C_2 \cdot e^{-r_2 t}$$

where  $C_1$  and  $C_2$  are the fast and slow-decay fractions respectively, and  $r_1$  and  $r_2$  the corresponding values of  $r$ . In Gonzalez and Sauerbeck's (1982) results for Costa Rica soils,  $C_1$  ranged from 52-72% of total carbon and  $C_2$  correspondingly from 28-48%. Values of  $r_1$  were mainly in the range 3.4-7/4, those of  $r_2$  in the range 0.12-0.23. Jenkinson and Ayanba's (1977) values for Nigeria are similar.

Three lines of evidence suggest the existence of a third organic matter fraction, with a considerably slower rate of decay. First, it is possible to calculate the equilibrium value of soil carbon, based on the existence only of the first two fractions. The theoretical equilibrium calculated in this way is found to be about 1.5-3.0 times the annual addition of plant material. Observed soil carbon percentages, however, are very much higher, such as to imply a totally unrealistic value of annual plant fractions. This leads to the presumption of a third fraction, with substantially slower decay.

The second piece of evidence comes from the decay of non-labelled carbon in the same experiments as those described above, that is, carbon already present in the soil at the start of the experiment. This is lost very much more slowly than the labelled carbon; typical values appear to be some 3% per year, a similar value to the formerly - assumed decomposition constant. This unlabelled soil carbon may be taken to comprise a mixture of relatively recently-added plant carbon and older material, and thus the loss rate of the latter is likely to be less than that of the total carbon.

Thirdly, there has for long been the apparent anomaly that carbon dating of soil organic matter has sometimes yielded values of hundreds of years. This could refer to the third, very stable fraction.

Thus there appear to be three organic matter fractions:

- a fast-decay fraction with a half-life in tropical soils of less than 6 months; this may alternatively be treated in modelling as loss during humification;
- an intermediate-decay or labile fraction with a half-life in tropical soils of about 3 years.
- a slow-decay or stable fraction, capable of remaining in the soil for periods in excess of 50 years.

The first two fractions are clearly likely to be the main contributors to nutrient release. It has been speculated that the third fraction contributes

particularly to maintenance of favourable physical conditions in the soil, but there is no evidence for or against this.

Does the stable fraction originate mainly from decay of lignin, and is it thus favoured by woody litter? If so, there is an obvious significance for agroforestry. There is also a management implication, namely that twigs and fine branches should be left to rot with leaf litter, and not removed for convenience of agricultural operations.

Whatever the detailed mechanisms, it is plausible to suppose that litter of differing quality affects soil biology in varying ways, one of the basic hypotheses of the TSBF (Section 2). If this is so, then there is clearly a potential value in the capacity of agroforestry to yield a mixture of herbaceous and woody residues.

### **The role of roots**

The second advance in knowledge, also found by C labelling, is that root exudation and root death during the growth of a plant, taken together, can substantially exceed the mass of roots found by digging up the plant and weighing what remains (Sauerbeck and Johnen, 1977; Bowen, 1984). That is, more labelled carbon remains in the soil over a period that can be accounted for by the roots present at the end of that period. This may help to explain why the soil organic matter situation under agriculture is not even worse that it might be!

We do not know if tree roots are more active or less than those of herbaceous plants in this respect. There is a potential significance, likely enough to be worthy of investigation, in the fact that trees produce a mixture of different types of roots, which could be beneficial in a similar way to that of a mixture of different types of above-ground litter.

## **RELATED TOPICS**

### **Interactions in time and space: the relevance of soil rest period requirements**

The situation in which a period of annual crops is alternated with a fallow or other means of restoring fertility has been reviewed in terms of soil rest periods (Ahn, 1979; Young and Wright, 1980). A rest period is defined as natural fallow, grass ley or managed woody fallow. The rest period requirement is the proportion of rest time needed to maintain the soil in a steady and productive state, when used for cultivation of annual crops. The requirement is expressed in terms of the cultivation factor, R, the number of years under cropping expressed as a percentage of the total cropping/non-cropping cycle.

A review of available information on rest period requirements was conducted as part of the FAO study of crop production potential of agro-ecological zones. Data were obtained both from published information and a questionnaire. Rest period requirements were obtained according to climate, soil type and level of agricultural inputs (Young and Wright, 1980). Low inputs refer to traditional farming methods without use of fertilizers, intermediate inputs to improved farming but with moderate technical and capital resources, high inputs to advanced technology. A summary of the results is given as Table 5.

This review was conducted in terms of rotations in time. It is important for agroforestry to know whether the results would remain the same if transplanted into spatial terms. For example, for ferralsols in the rain forest zone under low inputs, the R value is given as 15%, a requirement of 6.67 years of fallow to every one of annual crops. Translated into spatial terms, this implies that to maintain soil fertility, the tree strips would have to cover 85% of the land, leaving only 15% for crops. This is acceptable under a taungya system, but certainly not for alley cropping. For luvisols in the savanna zone at intermediate input levels, the rest period requirement is 50%, equivalent in the alley cropping system to equal widths of crop and tree rows.

These results deserve careful notice, particularly in the planning of alley cropping. If it appears, whether by reference to logical experience or from Table 5, that the rest period needed to maintain fertility in a cultivation fallow rotation is X percent of time, then the initial assumption must be that to achieve the same result in a spatially-based system, X percent of the land must be occupied by trees. If it could be shown that a given percentage of tree cover grown at the same time as crops had a more beneficial effect on fertility than an equal percentage of time in fallow, then this would be of great significance and potential benefit. Unless and until such evidence is forthcoming, however, the null hypothesis must be that the tree cover required to maintain fertility is proportional to the fallow period found to be necessary.

#### **The use of tree litter for purposes other than fertilization**

Throughout the discussion, it has been assumed that all parts of the tree are returned as litter to the soil. In agroforestry systems this frequently will not be the case. The larger branches and, on felling, the stem will commonly be harvested as fuelwood, the leaf litter and reproductive parts (e.g. legume pods) may be fed to livestock. Many agroforestry systems are designed and practised precisely with the objective of helping with these supply problems. If fuelwood or fodder are in short supply, and labour sufficient, most farmers will choose to harvest these tree products. The above-ground woody and/or herbaceous residues are not then available to maintain soil fertility.

In the case of fuelwood, there could be a partial return of nutrients if the ash is returned to the soil, but a permanent loss of carbon. In the case of cut-and-carry fodder, the cycle is closed if the kraal dung is returned to the fields. Since livestock are a source of farm income it may well prove to be more beneficial combining economic with ecological aspects, to pass litter through the digestive systems of livestock than to apply it directly to the soil. Many farmers will do so anyway, without the need for analysis of benefits by linear programming!

#### **Erosion control**

Although data from the tropics are still sparse, there is clear evidence of a link between soil erosion and fertility decline (Stocking, 1984). Material lost by sheet erosion contains a disproportionately high content of nutrients, compared with the topsoil as a whole. There is also loss of soil organic matter, the highest content being at the surface, as well as the washing away of litter prior to its decomposition. The quantitative relations between erosion rates and fertility loss are poorly known but need to be taken into consideration in models of nutrient cycling and maintenance of fertility.

**Table 5:** Rest period requirements of tropical soils. All values refer to the cultivation factor, R, expressed as a percentage. Source: Young and Wright (1980).

Soil type (FAO)	LOW INPUTS			INTERMEDIATE INPUTS			HIGH INPUTS			
	Growing period (days)	Rain Forest Zone 270-365	Savanna Zone 120-269	Semi-arid Zone 75-119	Rain forest Zone 270-365	Savanna Zone 120-269	Semi-arid Zone 75-119	Rain forest Zone 270-365	Savanna Zone 120-269	Semi-arid Zone 75-119
R, Q Regosols and Arenosols		10	15	20	30	35	45	50	65	50
F Ferralsols Fa acric		15 5	15	20	35 10	35	40	70 60	70	75
A Acrisols		15	15	20	40	35	60	65	65	75
Luvissols		25	30	35	50	50	55	70	75	75
B Cambisols		35	50	40	65	60	60	85	85	80
N Nitosols Nd dystic Ne eutric		25 40	30 55	40 75	55	80	70	90	90	90
V Vertisols		40	55	45	70	75	75	90	90	90
J, G Fluvisols and		60	70	90	80	80	90	90	90	90

The main agroforestry techniques for soil conversion are as follows:

- planting trees on the risers of terraces (for both stabilization and production);
- planting trees on contour bunds or strips (mainly to make productive use of this land, but also to ensure that these remain in fixed positions);
- using closely spaced hedges as conservation barriers.

The third of these in particular can be combined with fertility improvement, since the hedges are kept low by repeated pruning. Prunings from the other two techniques can also be thrown onto the soil between rows of trees, thus combining fertility maintenance with physical soil conservation, and the necessity of pruning the trees to prevent excessive shading.

### REQUIREMENTS FOR RESEARCH

It has not yet been demonstrated that the desirable situation shown in Figure 3, the combination of crop production with maintenance of soil fertility in a steady state, can be brought about; nor is there proof of the other possible beneficial effects of trees upon the soil that have been discussed. The purpose of this paper is to put forward hypotheses which have highly attractive consequences if they can be verified. These hypotheses need to be tested by research.

There is now a substantial amount of ongoing research in agroforestry, and a growing body of completed results. Comments on this research are first, the existence of a bias towards alley cropping, and secondly too much emphasis on a pragmatic approach at the expense of a basic understanding of processes.

The bias towards alley cropping is explicable in the light of scientists' preference for controlled conditions and the opportunity to change variables (e.g. spacing) in a regular manner. There has been relatively little work on boundary planting — and whoever heard of research on the highly productive, practicable and extremely sustainable system of home gardens? This bias is understandable and perhaps excusable, except that alley cropping must not be regarded as a panacea.

More serious is the emphasis on pragmatic research, on the approach of 'try it and see if it works'. The reason for this is the desire quickly to produce a technology that can be put into practice. This in turn stems first, from the worthy idea that research is for the benefit of farmers, and secondly, from pressure by aid agencies to go ahead with development as soon as possible.

The outcome is that too much current research leads to uncoordinated ad hoc results, rather than a basic understanding of the processes involved. This is illustrated by alley cropping experiments, on species and spacing designs, in which the results are evaluated solely in terms of crop yields, without monitoring changes in soil. This black box approach — and the soil ecosystem is inside the box — leads to results that cannot be extrapolated or manipulated. They show that certain combinations of species, spacing and plant management will work well in a particular environment; but through omitting to demonstrate why these function well, and why other combinations do not, this fails to supply the means for scientific design of other combinations for different circumstances.

This comment applies to many aspects of agroforestry research including soil biology and fertility. The basic understanding that is needed in this field is the mechanisms by which trees improve the soil. The field design of such experimental work should be based on experimental plots with:

- trees only;
- crops only;
- mixtures of trees with crops.

Plant growth, litter production and decomposition, and soil changes are monitored under each of these. Only the mixtures are in themselves agroforestry; but frequently, advances in knowledge needed for agroforestry design are obtained from research based on monocultures.

For the monitoring observations under such a design, the 'minimum package' devised by the TSBF programme forms an excellent basis. Because of high micro-variability of soil properties, a statistical design based on composite sampling is necessary. The significance of results can be calculated in advance on the basis of coefficients of variation of individual soil properties from single samples of some 30 - 70%. The soil monitoring programme at the ICRAF Machakos Field Station employs such a sampling design, although as it is a station for demonstration and training, it is currently monitoring mixtures only, without monoculture controls (Young, 1984).

Another way of expressing the position is to say that an understanding of how agroforestry techniques can best be applied to raise soil fertility will come from two sets of research; first, the broad range of soil biological research, leading to an understanding of basic processes; and secondly, studies of the specific effects of mixtures of woody and herbaceous litter, of different types of roots, and thus of trees and herbaceous plants.

At present, much pragmatic research is inefficient, partly because a high proportion of the species/spacing/management combinations tried are unsuccessful, but mostly because they do not lead to an understanding of the mechanisms involved. If a basic understanding of processes can be built up, then 'try-it-and-see' work, which is also necessary as a final predevelopment stage, can start from a much more advanced position, with a good prediction of what can be expected to succeed.

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### 3. EFFECT OF TREES ON UPLAND ANNUAL AGRICULTURE IN THE LOW COUNTRY DRY ZONE OF SRI LANKA

J Handawela

Agricultural Research Station, Angunakolapelessa, Sri Lanka

#### SUMMARY

- (1) As an alternative to shifting cultivation on eluvial land, cropping of a degraded upland under simulated forest conditions was attempted.
- (2) Annual crop performance, soil properties and weed flora and density were compared with and without simulated forest of Gliricidia maculata.
- (3) Simulated forest plots had the following advantages over the plots without simulated forest:
  - (i) Better crop plant growth and higher crop yield at low N levels;
  - (ii) Better infiltration and less surface ponding following rain;
  - (iii) Lower soil hardness in surface layers enabling easy tillage;
  - (iv) Lower proportion of problem weed species.

#### INTRODUCTION

Soil in the low country dry zone of Sri Lanka consists mainly of a catenary association of upland Ustalfs and lowland Aqualfs. Aqualfs, being accumulative are essentially rich and hence are ideally suited to lowland paddy cultivation.

Ustalfs suffer leaching in wet weather and fast decomposition of less stable material specially when the insulating forest layer is removed. Therefore, in this ecosystem, biomass plays a key role as an available nutrient reserve. In shifting cultivation, forest is felled to harvest this reserve for use in crop cultivation. Following felling and burning of forest, reserves of available P, available S, Ca, Mg, K and N added to soil become depleted with every advancing cropping season.

Along with this chemical impoverishment, soil tilth deteriorates, and weeds become more competitive. These factors collectively compel the shifting cultivator to abandon unproductive fields.

In this investigation, a new method that aims at solving or circumventing the cause of low productivity of eluvial lands is attempted. It, as in shifting cultivation, accepts the usefulness of live biomass as an ecological stabilizer. Trees are grown to simulate forest conditions as best as possible and to perform the same functions of the forest fallow in shifting cultivation. For this reason the proposed method is called "Agriculture under Simulated Forest".

Under this new system, soil in the eluvial part of the catena is treated more as a mechanical support for crops rather than as a source of nutrients. Nutrients are held by live biomass and are applied to crops at a time calculated to meet the latter's peak nutrient requirements. As soil is not trusted as nutrient store even for short periods, tree loppings (through which the nutrients

stored in tree biomass are transferred to soil for use by crop plants) are given just enough time to decompose and release the nutrients locked therein before the crop plants reach their time of peak nutrient requirement.

## MATERIALS

A block of eluvial land on a valley side slope that drains to Maha Illuppallama tank was selected for this study. It belongs to the Agriculture Research Station at Maha Illuppallama and presumably had been cleared from forest at least 50 years ago. It probably had been subjected to many unsuccessful attempts with upland agriculture. The land composed of eluvial soil, had been graded in 1968 to terraces and by 1976 it was in an abandoned state under unmanaged Brachiaria brizantha grass.

## METHODS

### Preliminary Preparations

In 1977, the leguminous tree species, Glyricidia maculata, was planted in a square design at a spacing of 5m by 5m. This design was altered in April 1980 to a row design with a higher tree density, rows spaced 5m apart and trees spaced 1m apart within each row. Planting material used was 2.5m long cuttings.

### First year of field experimentation

The first experiment with a field crop was established in October 1980 using the loppings from the trees planted in 1977. It was a simple experiment on a randomised block design with one limitation, control plots with no trees had to be on one end of the replicates, for all the replicates. Each plot was 25m by 20m and 4 treatments were tested (Table 1). There were 4 replicates.

The field was hoe-weeded in September 1980. The canopy of the trees planted in 1977 was about 1m in radius and it offered some shelter to the operators from the mid day heat of September, during weeding. Maize was planted in October after a few rains had provided enough moisture to wet the soil profile. The whole land area was planted as in monocrop cultivation and no special space was spared for the trees. Thus planting density and plant population per hectare of the crop were the same as in monocrop maize cultivation.

About 10 days from germination of maize seed, trees were lopped at a height of 2m from ground level and loppings were placed between the maize rows. For fertilizer plots, basal fertilizer was added with this operation. Any new branches that developed after this pruning were regularly removed and added as mulch to the ground surface. Top dressing of fertilizer that is usually due in 45 days from planting was accordingly applied to the fertilizer plots.

Growth of maize was watched and when it reached a stage at which it no longer required sun light, moisture or nutrients, pruning of trees was suspended and the trees were allowed to grow while the maize crop was still in the field. Height and colour of maize plants was recorded using the standard procedures.

TABLE 1: Effect of fertilizer and simulated forest conditions on crop performance and soil properties in eluvial land during the first year of experimentation

Treatment	Plant height cm @	Dry matter yield kg/ha*** Straw	Grain	Loppings added kg/ha <sup>-1</sup>	Soil chemical properties (surface soil) pH	E.C. mmhos/cm	Organic matter %	Total nitrogen %
1. Control, no simulated forest, no fertilizer	174	1145	1163	-	5.92	0.025	1.29	0.076
2. Simulated forest, no fertilizer	185	1334	1373	561	5.92	0.031	1.43	0.104
3. Simulated forest, P <sub>2</sub> O <sub>5</sub> 60 kg/ha, K <sub>2</sub> O 60 kg/ha	216	1493	1841*	663	6.13	0.040	1.59	0.105
4. Simulated forest, N 60 kg/ha, P <sub>2</sub> O <sub>5</sub> 60 kg/ha, K <sub>2</sub> O 60 kg/ha	225	2035	3002**	579	5.94	0.040	1.57	0.089
Average	200	1502	1845					
C.V.%			18.74					
L.S.D. at 5% probability			553					
L.S.D. at 1% probability			794					

@ at cob maturation, \*\*\* at 14% moisture, + 70°C dry, \* significant at 5%, \*\* significant at 1%

At harvesting only the maize cobs were removed from the field and straw and stubble were left on the soil surface. The trees were allowed to grow uninterrupted.

### **Second year of field experimentation**

In order to eliminate any interplot differences that may arise from fertilizer added to some plots during the first year, gingly (Sesamum indicum) was sown throughout the land with rains in March/April, 1981. No fertilizer was added to this crop. Tree growth from early January 1981 was pruned and the loppings were added to gingly crop in the tree plots. The trees were maintained in a pruned state as long as gingly needed sunlight, soil moisture and nutrients for growth.

Making use of the tree growth from May 1981 the experiment proper was commenced in September/October 1981. By this time there was a bigger biomass in tree plots than in the year before because the trees planted in 1980 too had grown to some size. Two separate experiments were conducted, one under simulated forest and the other on bare land. Both were of randomised complete block design with 4 treatments (Table 2) and 4 replicates. The individual plots in the experiment under simulated forest conditions were 15m by 15m and the bare plots were smaller, 15m long and 5m wide. Both experiments were located on the same contour adjacent to each other to guarantee comparability of soil between the two.

After weeding with the hoe in September and early October, maize seed was planted in mid October. As in the previous year, 10 days from planting of crop, basal fertilizer was applied to fertilizer plots and the trees were pruned and loppings mulched in the tree plots. Top dressing of fertilizer due on 45 days from planting was given to fertilizer plots.

Plant height and plant colour were recorded at appropriate times. The trees were maintained in a pruned state to allow the maize crop to grow without any competition for sunlight, moisture and nutrients by the trees. When the maize crop had reached a stage at which it no longer required the above supplies, the trees were allowed to regrow.

Cobs were harvested from the mature maize crop. Straw and stubble were left in the field to mulch the ground.

### **Growth rate of Glicicidia trees after pruning**

In order to determine the optimum pruning interval of Glicicidia trees, the length attained by growing new shoots was recorded. Seventy two trees were randomly selected and in each the length of 3 shoots was monitored over a period of 3 months after pruning.

TABLE 2: Crop performance in eluvial land with and without simulated forest during the second year of experimentation

Treatment	Loppings added kg ha <sup>-1</sup> +	Crop dry matter yield kg ha <sup>-1</sup> ++		Plant height cm@	Soil strength kg/cm <sup>2</sup>
		Straw	Grain		
With simulated forest					
1. No fertilizer	2811	3190	1561	127	1.06
2. N 60 kg ha <sup>-1</sup>	3129	3134	1921 ns	133	0.87
3. N 60 kg ha <sup>-1</sup> , P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup>	2986	3470	2476 ns	146	1.00
4. N 60 kg ha <sup>-1</sup> , P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup> , K <sub>2</sub> O 60 kg ha <sup>-1</sup>	2963	3190	2728 ns	152	1.06
Average	2972	3246	2172	139	1.00
Without simulated forest					
1. No fertilizer	-	2126	680	94	1.69
2. N 60 kg ha <sup>-1</sup>	-	2238	1385**	99	1.87
3. N 60 kg ha <sup>-1</sup> , P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup>	-	2070	1251**	92	1.56
4. N 60 kg ha <sup>-1</sup> , P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup> , K <sub>2</sub> O 60 kg ha <sup>-1</sup>	-	2726	1354**	100	1.81
Average	-	2290	1168	96	1.73
L.S.D. 1%			542		

+ at 70°C, ++ at 14% moisture, @ 50 day old plants, ns not significant, \*\* significant at 1% probability

### **Soil chemical properties**

Although it is still too early to look for differences in soil chemical properties, soil pH (1:2.5 water), electrical conductivity (1:5 water), soil organic matter and total nitrogen were determined in late April 1981, about 6 months after initiating the first field experiment with crops.

### **Soil tilth**

In addition to the ameliorating effects provided by trees during weeding prior to crop planting, the soil in tree plots was found to be offering less resistance to tools. In order to check this, soil in tree plots and in bare plots was tested for unconfined compressive strength in March 1982. The instrument used for measuring this soil property offered a plane surface of 0.25 square inches. The force at which the soil surface gave way when this plane was pressed against soil was recorded as the unconfined compressive strength of surface soil.

## **RESULTS AND DISCUSSION**

### **Initial condition of the land**

The degraded condition of the land before commencement of the experiment is clear from the following soil characteristics. soil pH (1:2.5 water) 5.98, electrical conductivity of soil (1:5 water) 0.035 mmho/cm, soil organic matter 1.47% and total nitrogen 0.08%.

### **First year of experimentation with field crops**

The results of the first year of experimentation clearly show response to fertilizer, particularly nitrogen, and insignificant response to biomass added from trees (Table 1). This confirms the eluvial nature of the land and the fact that the small amount of biomass averaging to about 600 kg/ha added is not enough to have any impact on the productivity of degraded land. Also the period during which the land had been under this small biomass cover may have been too short for there to have been any cumulative protection to the soil. Therefore this experiment can be interpreted as illustrating the inadequacy of insulation and of the amount of biomass that is produced by few young trees to compensate for the degradation that had been going on in this land for many years.

### **Second year of experimentation with field crops**

Results of the two experiments, with and without a perennial tree component are presented in Table 2.

In the experiment under simulated forest conditions, the observed yield increase in response to added fertilizer is not high enough to be statistically significant. This is because even the treatment without fertilizer has a satisfactory yield that results from the effect of the trees and their loppings. This shows that when a crop is grown in eluvial land under simulated forest conditions as in this experiment there is no particular need for application of fertilizer.

The results of the experiment in bare land that was not afforded with the protective role of simulated forest clearly show that bare soil is a poorer source of nutrients and when fertilizer is added to such a soil the crop yield can be improved.

Therefore what emerges from the two experiments is that the soil in eluvial land is a poor supplier of nutrients and that for it to produce good yields it needs nutrient supplies either through organic recycling or through fertilizer application.

Although comparison of two different experiments is not sound statistical practice, it may not be unreasonable to compare the above two experiments for identical treatments were tested in both, and both were managed in the same manner and located adjacent to each other on the same contour. Higher average grain yield, higher straw yield and taller crop plants in the experiment under simulated forest may be taken as indicative of the supremacy of agriculture under simulated forest over agriculture on bare land.

### **Pruning cycle of perennial trees in plots under simulated forest**

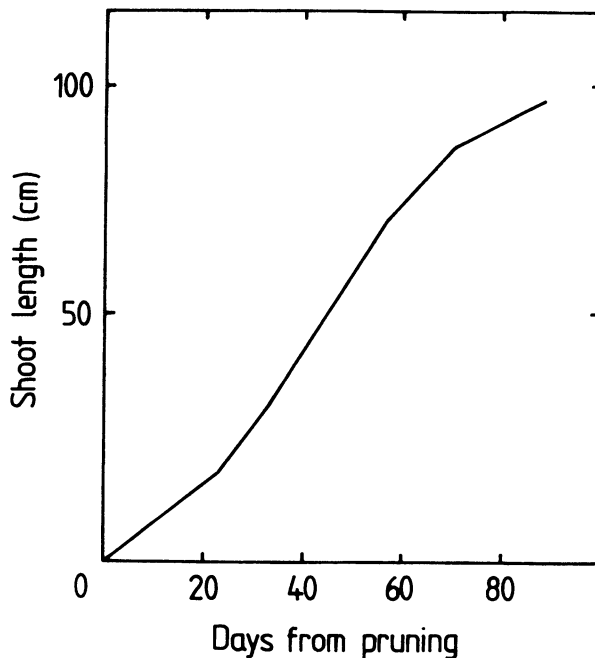
The length of growing *Gliricidia* shoots when plotted against time makes a sigmoid curve (Figure 1). Within the first 3 weeks of shoot elongation after pruning they grow at a rate of about 0.83 cm a day. This is followed by a period of rapid elongation at a rate of about 1.54 cm/day for almost 6 weeks. Over the next 3 weeks the rate of growth slackens down to 0.57 cm/day. Beyond this stage, the growth rate tends to level off. Therefore for highest dry matter production from these trees, the best pruning interval appears to be about 10-12 weeks. Coupling this finding with other considerations such as rainfall pattern, crop needs for nutrients and insulation offered by tree canopy to both soil and field operators, tree pruning for the October cropping season is best done after planting the crop. One important consideration is not to prune too early before the crop plants are ready to take up the nutrients released from decomposing loppings.

After this initial pruning the trees are maintained in a pruned state in order to maintain the best of conditions for crop plant growth without any tree induced competition for soil moisture, nutrients and sunlight. When the crop has reached physiological maturity there is no fear of the tree competing with the crop for inputs, and from this point onwards the tree component can be allowed to grow. In the cropping pattern of the eluvial land in the dry zone region, the crop plants reach physiological maturity by early January, and after this time it is possible to let the trees regrow. The objective of this regrowth is to afford the soil cover after the crop is harvested and to establish a medium for locking up nutrients that are released for decomposing crop residue.

The branches that begin regrowth in January are generally ready for lopping in March. It would, however, be beneficial to keep the branches on until after the April crop is sown so that the tree canopy can protect the soil from rain till the crop is ready to assume a protective role. The trees are pruned after the crop plants have established themselves, and thereafter top priority is given to the needs of the crop. Trees take over when the April grown annual crop is physiologically mature and continue to perform the soil protecting and nutrient conserving functions till the next rainy season in October.

Thus the pruning procedure of trees is aimed at maintaining a continuous cycle or relay between the physiologically active tree and the physiologically active crop (Figure 2). The purpose of this relay is not only to harbour soluble nutrients in the biomass but also to afford insulation and protection to soil and man from the harsh tropical climate.

Figure 1  
Pattern of Gliricidia shoot regrowth after pruning



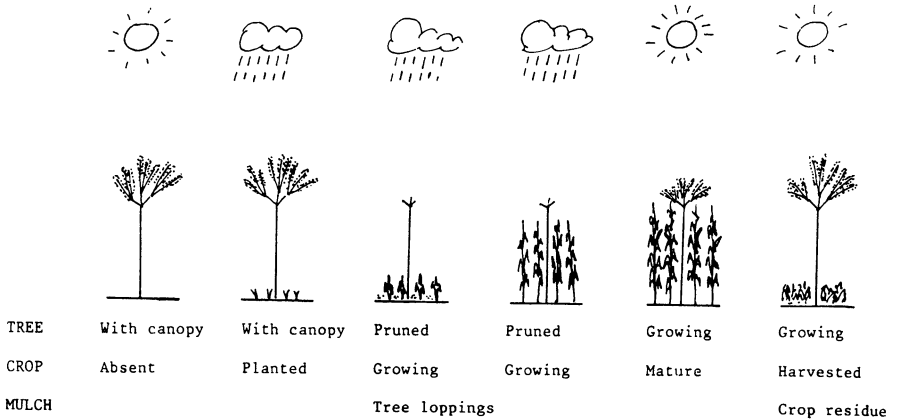
#### **Soil chemical properties**

Even at this early stage of experimentation with limited amounts of tree biomass, the surface soil of tree plots shows some improvement over the bare plots. The former soil has slightly more organic matter and total nitrogen and a slightly higher electrical conductivity (Table 1).

#### **Soil tilth**

Unconfined compressive strength of surface soil is reported in Table 2. The soil strength figures show that surface soil in tree plots has a better tilth than in the bare plots. This is perhaps due to better protection received by the soil in tree plots from tropical sun and rain and higher activity of soil fauna in tree plots. During rainy weather there were more earthworm casts in the tree plots than in the bare plots.

Figure 2: Diagrammatic presentation of relationship between simulated forest and annual crop in relation to change in weather over a cropping season.



### Nature and management of simulated forest

The two main roles played by the trees that make up the simulated forest could be conservation of the plant nutrients available in the ecosystem within the tree biomass and protection of soil from harsh tropical climate. The former arrests leaching of nutrients that are released to the soil by rock weathering and decomposition of organic matter. The latter helps the soil to acquire a good tilth and arrests erosion. It also helps to smother weeds. If the trees include leguminous species they could also fix atmospheric nitrogen and store more nitrogen in the biomass.

Trees can yield other benefits such as fruits and timber of economic value. For the purpose of this study which is exclusively for growing annual agricultural crops in eluvial land there is no need to be concerned with such aspects. For the same reason, considerations such as perpetuation of species and variety and heterogeneity of natural forest flora are not of direct relevance to this study.

This canopy of the simulated forest must be dense enough to lock up enough nutrients for circulation into the succeeding crop and to provide sufficient insulation to soil. It must also be light enough to allow easy handling.

In the first year of this investigation, 600 kg ha<sup>-1</sup> of dry matter added was too little to be of any help for crop cultivation. In the second year of operation the dry matter added via loppings in October 1981 amounted to almost 3000 kg ha<sup>-1</sup> (Table 2). Analysis of the loppings for nitrogen gave an average value of 3.63% on a 70°C dry basis (range 2.83%-4.11%). On this basis 3000 kg of loppings contain about 108 kg nitrogen. From Table 2 it is clear that the tree plots that got additional nitrogen fertilizer produced higher yields than the tree plot that got no fertilizer even though the increase in yield is not statistically significant. From this we can see that 3000 kg of dry matter per hectare is still too little. During the operation of this experiment many of the trees were still too small. Therefore it is too early to say whether the stand of 1 tree/5m<sup>2</sup> is too low a density. Increasing tree density is easy but before doing so it must be assessed whether increased tree density would interfere with farm operations.

According to Nagarajah and Amarasiri (1977) Gliricidia maculata leaves on an oven dry basis have 4.15% N, 0.27% P and 1.30% K. On this basis 3000 kg of loppings add close to 8 kg/ha and 39 kg/ha of P and K respectively. The low figure of P does not imply any adverse effects because over the years the soil at Maha Iluppallama has become saturated with phosphorus from annually added fertilizer. In common with other government managed farms, the soil at Maha Iluppallama does not show response to fertilizer phosphorus. Other lands of course show phosphorus deficiency but it can be easily and safely corrected because of the relative safety of phosphorus from leaching and relative scarcity of sesquioxides that can fix it.

Pruning height of trees was fixed at 2 meters from ground level for two reasons. If branches emerge at a height below 2 meters they can interfere with field operations. If pruning is attempted above 2 meters, the pruning operation would be a difficult one. Also if the tree stump is shorter than 2 meters (as it can be if pruned at a lower level), it has little use if and when it is removed from the field. Gliricidia stems that are mature and are at least 2 meters long have a demand as fence posts.

It is important to explain why the little documented Gliricidia maculata was used instead of the much publicised Leucaena leucocephala (National Academy Sciences 1977). Gliricidia maculata needs less introduction to the local farmer. Its leaves have more nitrogen than Leucaena. It also does not contain the toxic amino acid, mimosine, which Leucaena is noted for. The straight branches of Gliricidia are more amenable to handling than the bent and twisted branches of Leucaena. Most of all, the Gliricidia tree population can never proliferate into menacing dimensions because the little seed it produces does not germinate that well. In fact, the accepted method of its propagation is by cuttings. Leucaena on the other hand is a prolific producer of viable seed and hence it harbours the threat of becoming a weed if ever its population is to go out of control.

If properly managed the simulated forest can set in motion a desirable cycle. The greater the biomass added to soil by it the better would be the growth of the succeeding crop. The larger the crop straw volume and the nutrients contained therein the more advantageous would it be for the simulated forest to regrow.

#### 4. LEUCAENA ALLEY CROPPING FOR THE KENYAN COAST

Bashir Jama, Amare Getahun, David Ngugi and Bill Macklin

Mtwapa Agroforestry Energy Centre  
Ministry of Energy and Regional Development, Kenya

##### SUMMARY

Leucaena leucocephala alley cropping was found to contribute to increased maize yields on sandy coastal soils. This was due to (i) the addition of the high Nitrogen-containing green leaf manure to the soil; (ii) other improvements in soil fertility, including increased carbon; and (iii) a significant decrease in weed populations.

Higher inter-row and intra-row densities of Leucaena were significant in both higher production of green leaf manure and greater increase of maize yields.

##### INTRODUCTION

Average yields of 900-1000 kg/ha of maize at the Kenya coast are low, despite good annual rainfall (1260mm). The major reasons for poor maize yields are poor soil fertility and weed infestation (Muturi, 1981, Anon. 1984). Weeds alone are thought to cause over 40% crop loss (Michieka, 1982). Soils at the coast are variable but are generally sandy loams, deficient in the major soil nutrients (N, P, and K), and have high rates of leaching.

Fertilizer application and/or use of animal manure is therefore recommended in order to realize good crop yields. However, both chemical fertilizer and animal manure are expensive and often not easily accessible. The recommended rate of animal manure application, 1.2 tons/ha/year (Grimes and Clarke, 1962) is high and typically not feasible for the small scale farmer.

It was against this background that alley cropping of maize with Leucaena leucocephala (hereafter referred to simply as leucaena) was initiated in May, 1982 at Mtwapa, and at Matuga the following year. Leucaena is a small leguminous multipurpose tree used for soil fertility improvement, fodder production, weed control and for woodfuel and poles. Alley cropping is a substitute for natural bush fallow and shifting cultivation which allows the land to be continuously and highly productive with a minimum of external inputs. There are many different alley cropping practices, one of the most promising of which is to establish permanent hedgerows of fast growing typically leguminous, shrub species in the crop fields. These hedgerows can be cut back during the cropping season. This practice can improve crop yields by improving land productivity through N fixation, leaf litter production, soil and water conservation, and weed control.

##### SITE AND METHODS

Leucaena leucocephala, variety K28, was planted in a parallel systematic design (Bleasdale, 1967) at Mtwapa in May 1982. Variable inter- (2, 4, and 8m) and intra- (0.5, 1, 2 and 3m) row spacings formed the major and the minor treatments respectively. This arrangement gives a split-plot design with 5

replicates each of 12 different planting arrangements (modules) as illustrated in Figure 1.

Cassava (*Manihot esculenta*) was used as the initial crop in the establishment of the leucaena. Both seedling survival and growth rates were high, possibly because the cassava provided an improved microclimate through its canopy which decreased water loss and discouraged weeds.

Maize (Coast Composite) was intercropped during the April 1983 long rains at a spacing of 90 x 30cm (one plant/hole), after the 1982/83 cassava crop was harvested. Green gram was then planted in the short rains (September-November) of that year. This maize/green gram rotation has been repeated each year since then and extensive data on their performance have been recorded each season. A control plot (without trees) is being maintained for comparison to these data. Recommended maize and green gram husbandry practices for the coast (eg weeding, fertiliser application and disease and pest control) are being followed, thus keeping the agricultural system constant and introducing the tree element as the only variable.

For the first 2½ years the leucaena trees were allowed to grow unmanaged and extensive mensurations were taken on their growth rates and associated crop yields for baseline data. These data are being used in assessing various leucaena management techniques presently being investigated.

Some of these data are presented below.

Each season soil samples are taken from each of the modules. These are analysed at the National Agricultural Labs for all major soil chemical properties. These data are then compared from season to season for changes in soil properties over time.

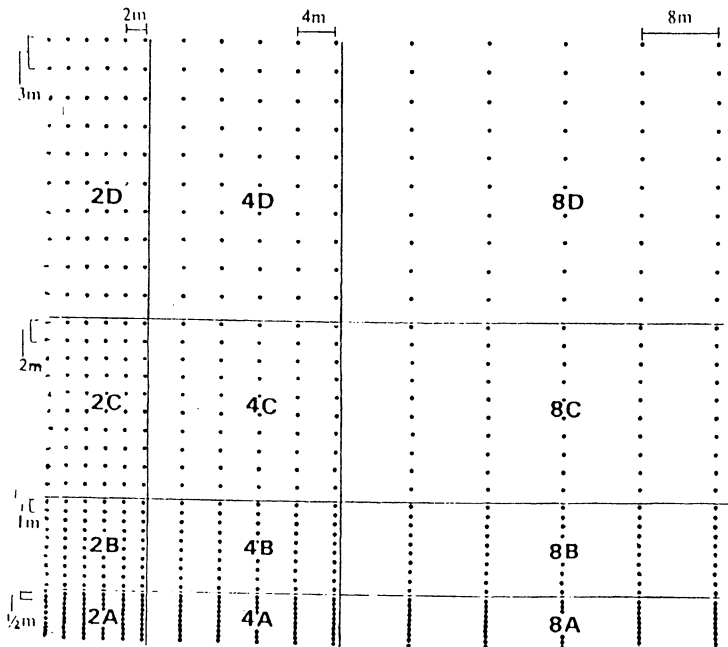
Weed control through leucaena is being investigated by estimating standing weed biomass in each of the modules. This is being done by taking the mean fresh weights ( $g/m^2$ ) of several randomly placed one-meter square quadrats in each of the modules. These measurements are taken before crop harvest.

The first management of leucaena was tried with the 1984 green gram crop. The trees were all pollarded through the complete removal of all side branches. However, though the associated crop was much improved over that with no tree management, yields were still depressed as compared to the control due to very vigorous regrowth and canopy closure. As pollarding was very labor intensive, a new management practice was experimented with in 1985.

This practice is similar to a system of coppicing that has been studied at the International Institute of Tropical Agriculture at Ibadan, Nigeria. In this practice, the leucaena were coppiced at 0.5m above the ground two weeks before the 1985 maize crop was planted. Leaves and twigs (under 5mm diameter) were incorporated into the soil of the maize plots, while the woody parts were removed for charcoal. The leucaena hedgerows grew back vigorously and thus had to be cut back at intervals of approximately one month during the development of the maize crop. Thus, the leucaena was coppiced again twice during the maize growing season. The green manure produced was incorporated into the soil on each occasion.

Figure 1: Layout of the Research/Demonstration Plots

Each '.' represents a tree. In each row there are 10 trees spaced  $\frac{1}{2}$  meter apart, 10 spaced 1 meter, 10 spaced 2 meters and 20 spaced 3 metres apart. After the first row, there are 5 rows that are 2 meters apart, 5 that are 4 meters apart and 5 that are 8 meters apart. This gives the 12 different planting arrangements, from very dense to very dispersed. The crops are planted based on the recommendation of the Ministry of Agriculture and Livestock Development regardless of the tree.



## RESULTS

### Maize Yields

Yields of the 1983 and 1984 maize and green gram crops before tree management was initiated were depressed. This was especially apparent in the 2 and 4m blocks. This is interpreted as being largely due to shade.

Coppicing trials in 1985 have, however, given much more promising results. The 1985 maize yields (kg ha<sup>-1</sup>) are shown in Table 1.

TABLE 1: Maize yields (kg ha<sup>-1</sup>) in leucaena plots, August, 1985, Mtwapa, Kenya.

Leucaena Inter-row Spacing (m)	Leucaena Intra-row spacing (m)				Mean
	0.5	1.0	2.0	3.0	
2.0	4,000.0	3,600.0	3,600.0	2,500.0	3,425.0
4.0	3,400.0	2,675.0	2,363.0	2,683.0	2,780.0
8.0	3,100.0	2,475.0	3,100.0	2,033.0	2,677.0
					Overall:
Mean	3,500.0	2,917.0	3,021.0	2,406.0	2,961.0
Control Plot Mean					2,526.0

C.V. (%) of Inter- row mean = 12

C.V. (%) of Intra- row mean = 28

The data in Table 1 indicate that this coppicing system shows much promise, as maize yields in the leucaena plots were generally higher than the control plot. Significant interaction (at 5% level) was found between the inter- and intra- row leucaena treatments on maize yields. In general, decrease in both inter- and intra- row spacing led to an increase in maize yields. These high maize yields are attributed to N-fixation by the leucaena (whose roots showed heavy nodulation) and therefore to the cumulative Green Leaf Manure (GLM) added and incorporated into the soil.

The contribution of below ground litter (roots) to soil fertility (and therefore to maize yields) has not yet been investigated.

### Leucaena Green Leaf Manure (GLM) Yields

Table 2 shows the cumulative leucaena fresh GLM yield (t/ha) for the 3 cuttings during the 1985 maize growing season.

TABLE 2: Cumulative leucaena fresh GLM ( $t\ ha^{-1}$ ) incorporated into soil, March-May 1985.

Inter-row Spacing (m)	Intra-row spacing (m)				Mean
	0.5	1.0	2.0	3.0	
2.0	28.3	17.4	13.9	11.3	17.7
4.0	18.3	8.6	6.5	8.2	10.4
8.0	12.1	6.2	4.6	4.8	6.9
Mean	19.5	10.7	8.3	8.2	

C.V. (%) of Inter-row mean = 17.3

C.V. (%) of Intra-row mean = 27.0

Significant interaction between inter- and intra- row spacings was noticed. The higher leucaena densities yielded more than the wider spacings.

This GLM yield represents leucaena growth of 5 months. Half of this period was during the dry season (December 1984 through March 1985). This growth was harvested on March 15th, before the maize was planted (wood biomass yields are presented in Appendix 2). Vigorous coppicing by the leucaena required it to be cut again 30 days later on the 16th April, and again 35 days later on 21st of May. On each occasion all leaves and twigs less than 0.5cm diameter were incorporated in the soil. As the corn crop had by then reached a substantial height (no longer in danger from light competition from the leucaena) the leucaena was not cut again during this cropping season.

This leucaena was allowed to grow till the beginning of preparations for the short rains crop in September 1985. Between May and September (4 months), the leucaena grew vigorously, producing not only large amounts of GLM, but also considerable fuelwood (see Appendix 2). Complete canopy closure of the leucaena occurred in both the 2m and 4m modules during this period resulting in weed control, and general soil improvement.

The GLM (leaves and twigs) being incorporated was analysed for nutrient composition to determine the potential nutrient contribution on a dry weight basis. Table 3 shows the nutrient composition of the GLM, while Table 4 shows the potential nitrogen contribution ( $kg\ ha^{-1}$ ) from this GLM to the intercropped plots.

TABLE 3: Mean nutrient composition of Leucaena GLM, March 1985, Mtwapa - Kenya\*

Percent Dry Matter						PPM			
N	P	K	Ca	Mg	S	Cu	Zu	Mn	Fe
4.4	0.3	2.2	2.2	0.2	0.3	11.9	21.0	51.0	216.0

\* Note that leucaena GLM can decompose into humus in only 2 weeks when incorporated (Kang, et al, 1981), thus releasing most of these essential nutrients.

TABLE 4: Potential Nitrogen Contribution (Kg ha<sup>-1</sup>) from Leucaena GLM (dry weight\*\* basis) April-August 1985 Mtwapa, Kenya

Inter-row Spacing (m)	Intra-row spacing (m)				Mean
	0.5	1.0	2.0	3.0	
2.0	284	174	140	114	178
4.0	183	86	65	82	104
8.0	122	63	47	48	70
Mean	196	108	84	81	

\*\* 1 kg dry weight - 4.4 kg fresh weight GLM

These high N-contributions from GLM were probably a major reason for the high maize yields from the trials. There was also substantial weed reduction and probable improved soil moisture (not measured in this experiment) due to the tree canopy during the dry season that contributed to the differential maize yields.

### WEED CONTROL

Significant weed reduction was achieved through the canopies developed between cropping seasons. As an example, the fresh weights (g/m<sup>2</sup>) of weeds harvested in August of 1985 are shown in Table 5.

TABLE 5: Mean effect of *Leucaena* treatments on weed fresh weight (g/m<sup>2</sup>), August 1985.

Inter-row Spacing (m)	Intra-row spacing (m)				Mean
	0.5	1.0	2.0	3.0	
2.0	68	38	30	54	47
4.0	70	60	170	130	107
8.0	230	133	163	147	168
					Overall:
Mean	123	77	121	110	108
Control Plot Mean					650

Weed populations in the plots were significantly lower than the control plot despite the absence of the tree shade during the cropping season (trees only form a canopy between crop seasons whereas during the crop seasons the trees are kept pruned). This weed reduction undoubtedly contributed significantly to the increased crop yields discussed in earlier sections of this report. As well, this effect would reduce the labour needs for weeding thus offsetting the extra labour required for *leucaena* management.

### Soil Fertility

Results of soil analysis from 1984 and 1985 are presented in Table 6. In general, there was a trend for increase in potassium, calcium, phosphorus and carbon over time and compared to the control. The pH values showed no definite trends, while the magnesium values showed a decrease over time, but an overall increase as compared to the controls. On the other hand, when comparing the modules to each other, no definite trends were apparent between treatments. That is, there were no apparent differences in the extent of soil improvement between the different tree densities. This was unexpected and these data will continue to be monitored in the future in order to better understand the impacts of the trees on soil fertility. However, as it is, the increased levels of soil nutrients indicated to date have undoubtedly contributed to the improvement of soil fertility and therefore to increased maize yields realised in August of 1985.

TABLE 6: Soil Analysis (Top soil) from the Leucaena Plots

Modules	Sample Dates	pH	K m.e. %	Ca m.e. %	Mg m.e. %	P p.p.m.	C %
	April '84	6.1	0.16	2.0		24.0	0.29
2M	Aug '84	6.08	0.24	2.58	1.55	18.0	0.45
	Jan '85	5.80	0.26	3.60	0.48	66.75	0.97
	April '84	5.9	0.14	1.6		22.0	0.26
4M	Aug '84	6.30	0.22	2.20	1.38	22.0	0.24
	Jan '85	5.98	0.24	3.40	0.80	31.75	0.87
	April '84	6.1	0.12	2.4		37.0	0.35
8M	Aug '84	6.32	0.24	2.78	1.80	29.0	0.40
	Jan '85	5.78	0.25	3.70	0.73	30.25	0.94
	April '84	-	-	-	-	-	-
Control	Aug '84	5.79	0.17	1.92	0.83	16.6	0.38
	Jan '85	5.83	0.23	3.10	0.40	32.25	0.49

### DISCUSSION

Many scientists have investigated the use of leucaena hedgerows/alley cropping as a soil improvement system in which crop yields can be sustained at relatively high levels without the addition of high amounts of chemical fertilisers (Torres, 1984). Such a system is self sustainable in terms of soil fertility maintenance, and also contributes to reduction of soil erosion, weed infestation, and tillage requirements.

Other studies have shown that the production potential of leucaena appears to be higher when associated with agricultural crops than when planted alone (Gill, 1982). This is probably due to the leucaena benefiting from crop management practices. (However, this may not be true for perennial grasses such as sugar-cane and napier grass which have depressed leucaena yields, especially if simultaneous establishment is attempted instead of giving Leucaena a head start). Kang et al (1981 and 1985) investigated the effectiveness of leucaena GLM as N-source for maize in Nigeria and reported a 40% increase in yields as compared to the control plot (maize alone) with the application of 10 tons fresh GLM or a combination of 5 tons GLM and N at 50 kg/ha. The GLM as an N fertilizer source appeared most effective when incorporated than when

applied as surface mulch. In our trials, an increase in maize yield of up to 58% was realised depending on the leucaena inter- and intra-row spacing (Table 1). This was felt to be due in part to the incorporated GLM which contributed as much as 284 Kg/ha of potential nitrogen from three cuttings during the maize cropping season in 1985.

Besides GLM, biological nitrogen-fixation is another important attribute of leucaena. Under favourable year round conditions, nitrogen fixation rates as high as 500-600 kg/ha/year have been measured (Guevarra, 1976). In our experiments, maize plants (rows) close to the leucaena row were consistently taller, on the average, than those farthest away. Those height differences were reflected in higher crop residue (stover) yields in the leucaena blocks (Appendix 4).

Considerable weed reduction was realised in the leucaena plots. Thus, leucaena alley cropping, particularly at narrower inter- and intra-row spacings (eg 2 x 0.5m or 4 x 0.5m) could contribute to increased maize yields at the sandy coastal strip of Kenya through GLM, nitrogen-fixation and biological weed control.

These trials need to be continued in order to confirm and clarify these results. As well, other species and leucaena cultivars need to be tried in these experiments. The results presented here show the potential that agroforestry has in maintaining soil fertility and improving crop yields for farmers at the coast, thus indicating the importance of continuing these trials and presenting their results to the public.

### RECOMMENDATIONS

Leucaena establishment, that is, its initial rate of growth is slow. It also initially tends to be a poor competitor to weeds, and young leucaena are highly browsed and thus need protection. The following guidelines and recommendations should be followed if leucaena is being established in alley cropping at the coast:

1. Leucaena can be established by either direct seeding (pretreated seeds) or from seedlings along with an agricultural crop such as maize. The leucaena should be planted directly in the row of crop so that it will not be weeded out when the crops are weeded. This system provides leucaena with weed-free conditions, protection from grazing/browsing animals and benefits from the applied fertilizers, especially phosphorus.
2. It is necessary to allow the leucaena to become well established before initiating tree management. This will result in a strong and effective leucaena hedgerow that can withstand frequent cuttings with good biomass yields. In our trials the trees were allowed to grow over 24 months before being harvested, however, tree management could be started as little as 12 months after planting if the trees have grown well. It is recommended that first tree cutting not be started until the tree is at least 4m tall.
3. The cutting height of the leucaena practised in our trials was 0.5m above ground level, and this has worked well and thus can be recommended. However, other cutting heights could provide decreased labour by making management of the tree canopies easier.

4. For best results, GLM from each cutting should be incorporated into the soil and not as surface green mulch. However, if the GLM is allowed to sit on the surface for 24 hours before incorporation, better nitrogen utilization can be realised.
5. Leucaena should be allowed to form a good canopy between growing seasons in order to effect better soil moisture retention, good weed control, as well as enhanced minimum tillage.

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## **5. SOME LAND USE CONSIDERATIONS IN THE AMELIORATION OF SOILS BY TREES**

**MALCOLM DOUGLAS**

**Food Production and Rural Development  
Commonwealth Secretariat**

### **SUMMARY**

Whereas the integration of trees into the farming system has considerable potential for ameliorating adverse soil conditions under smallholder conditions, the following points need to be borne in mind.

1. Improved land use practices need to be designed within the context of the people they are intended for and are therefore area specific.
2. Traditional practices frequently have a sound basis and can offer guidelines to the direction in which improvements should be made.
3. Farmers' own perceptions on the benefits and use of trees may be different to the land use planners' and need to be understood and respected before appropriate recommendations can be made.
4. Soil conservation and fertility maintenance should be an integral part of any agroforestry practice but will frequently be achieved as the by product of a practice recommended to meet a more specific need of the farmer.

Improved land use practices for the amelioration of soils by trees for the smallholder should ideally be :

- a) Simple - so they can readily understood and adopted by farmers;
- b) Low cost - within the financial reach of farmers;
- c) Labour efficient - produce the maximum benefits for the labour expended;
- d) Productive - increase the total productivity of the system and maintain and increase food crop yields;
- e) Sustainable - maintain productivity over the long term.

### **INTRODUCTION**

In the process of developing ways in which trees can be used to ameliorate adverse soil conditions there is a need for much fundamental and basic research and many of the papers in this volume deal with aspects of this. The purpose of this paper is to try and promote an understanding and consideration of the socio-economic environment in which the results of that work will ultimately be applied. It is important that those engaged in fundamental research should retain an awareness of the context in which their findings and recommendations will be implemented as ultimately the benefits of such research will be measured by whether or not they are taken up and used. There are many

examples of research leading to technically sound recommendations which fail to be adopted by farmers because the socio-economic constraints on their adoption have been overlooked.

For the purposes of this paper I wish to concentrate on the situation of the small rural farmer. Those of us concerned with land use planning for small holders are seeking for ways in which we can help them to make the best use of their own land so as to satisfy as many of their needs as possible by advising on ecologically sound, sustainable, economically viable and socially acceptable farming practices. Therefore what we recommend must be suited to the environmental conditions of the area, ie. suited to the soils, slopes, climate etc. It must be sustainable in that it must be possible to use the land in the recommended way over the years without it becoming degraded. The recommended practices must be ones which if followed will result in greater returns for the resources of, for instance, labour, cash expended eg. increased income from cash crops, greater self-sufficiency of food and fuel-wood. A farmer is very unlikely to follow advice which in the short term reduces his/her income or food production even if in the long term it maintains soil fertility nor will he/she do something which has a high labour demand for what are seen as relatively limited returns. Whatever a farmer is asked to do must match with what he/she regard as acceptable, for instance it's unrealistic to recommend something that requires considerably more labour per day than is the normal practice, nor should extra labour be called for at a time of year that is traditionally set aside for social non-agricultural activities (Douglas 1984).

#### **CONSIDERATION OF EXISTING FARMING SYSTEMS**

As well as these basic principles, it's important to develop an understanding of the existing farming systems to recognise that the small farmer operates under specific constraints and has particular problems and needs. The farmer may well approach things from a totally different perspective to that of a Western orientated professional adviser or researcher, and whereas at first sight what he/she does may appear irrational, careful study will reveal a complex rationality behind a particular practice. Where traditional farming systems have been developed over many years, close examination will usually show that farmers have an intimate knowledge of their local ecological conditions and have developed farming practices and cropping strategies designed to exploit these within the limits of their own technology while minimising the risk to themselves. (See Richards 1985). Above all, traditional farming practices have evolved first and foremost to ensure that as far as possible the needs of the household's food supply will be met. Therefore greater importance will be attached to farming practices which will ensure some food production even in the poorest cropping season than those that would produce higher yields in a good year but could produce nothing in a bad year. This is one reason why farmers appear to stubbornly stick to low yielding traditional varieties in preference to the new higher yielding varieties available. They are fully aware of the limitations of their own varieties but cannot afford to risk all on the new ones.

The land use planner who attempts to change and improve the system without first seeking to understand the existing farming systems and the land use perceptions of the farmers is asking for failure. Improved land use practices therefore have to be designed within the context of the people they will affect and be capable of incorporation into and adaptation of the existing farming system (Stocking 1985).

## INCORPORATION OF TREES INTO EXISTING FARMING SYSTEMS

The above holds true for the incorporation of trees into smallholder farming systems where there exists considerable potential to use trees to improve soil conditions in the pursuit of increasing and sustaining agricultural production. The potential for using trees to ameliorate adverse soil conditions is highest where natural soil fertility is low and dependent on the soil organic matter fraction; where there is a high risk of erosion; and where the soil surface is prone to desiccation. On such marginal lands, the deliberate use of woody perennials, if properly integrated into the farming system, can enhance both land productivity and sustainability (Lundgren and Nair 1985) and has great potential as a land use practice for small farmer with limited access to purchased farm inputs such as chemical fertilizers.

A careful look at most traditional smallholder farming systems will show that trees are an integral component of them. In traditional shifting cultivation and bush fallow systems, the fallow period, when the natural woody vegetation reestablishes itself and thereby restores the soil fertility, is a deliberate and important part of the farming system, interacting both ecologically and economically with the crops grown in the cultivation phase (Lundgren, Nair 1985). In some such systems, farmers will select the areas to be cleared on the basis of the presence of particular tree species, believing crops will grow better where this species occurs. This may be because the tree is only found on the more fertile soils or itself directly affects the fertility status. Farmers may also deliberately impose a basic degree of management into the woody component of the bush fallow by ensuring that when clearing the land for cultivation:

- i. the tree stumps are left high enough to withstand the effect of burning the woody trash;
- ii. the side branches on the remaining trunks are lopped to allow light through to the soil and crops and
- iii. the tree roots are left intact so that rapid regeneration of the vegetation from the stumps is permitted, thereby reducing the time needed to restore fertility before the area can be used again (Wijewardene and Waidyanatha 1984).

In areas of low population density with acid soils of low inherent fertility such as the "miombo" woodland areas of parts of Zambia and Tanzania, bush fallowing is an ecologically sound, sustainable, economically viable and socially acceptable farming practice where trees are deliberately used as a means of ameliorating adverse soil conditions, ie low fertility. The challenge to the land use planner is to try and improve on this by selective introduction of faster growing, particularly leguminous species that will both improve the fertility status and reduce the length of fallow period required. This is important where population pressure has led to a reduction in the fallow period due to shortage of available land and where appropriate land use practices for permanent cultivation have yet to be developed or adopted by the farmers.

In settled areas with permanent cultivation, smallholder farmers will have generally retained a number of trees when the land was cleared for cultivation. This has not been done in a haphazard way. On the contrary they can be clearly observed to have selectively left trees that they believe do not compete seriously with neighbouring crops. Indeed these trees may even enhance the

growth of crops. The farmers can be observed to manage those trees by, for instance, pruning the side branches to reduce any shading effect. At the same time, preference will be given to species that yield produce that the farmer values, such as wood for fuel or construction, fibres, medicines, fruit etc. Where a farmer deliberately retains a tree that has an adverse effect on neighbouring crops you can be sure that this is because the particular species produces something of sufficient value to the user of the land that it will compensate for the loss of crop yield. The decision to leave trees in the farmland is a deliberate choice by the farmer even though he/she may not be able to fully explain the reason or benefits. It is interesting to note, from a rapid survey undertaken in Malawi, that of the indigenous trees deliberately retained by smallholders in their farmland, most were leguminous species and therefore likely to be compatible with and beneficial to crop farming (Poulsen 1981).

Some traditional farming systems, such as the home gardens characteristic of many wet tropical regions, show a sophisticated use of woody perennials. These home gardens are characterised by the intensive integration of numerous multipurpose trees and shrubs with food crops and animals, simultaneously on the same unit of land. A study of one such system, the Chagga homegardens of Mt Kilimangaro, North Tanzania, showed that as the native forest was settled, trees that provided fodder, fuel and fruits were retained while the less useful species were eliminated and replaced with new tree and crop species. The Chagga are skilled farmers with an intimate knowledge of the different crop and plant species in the home gardens and have evolved appropriate management techniques. These take into consideration their particular requirements for the various components of the system so as to optimise the total production. The large species diversity provides both subsistence and cash crops and enables the farmer to keep his/her management options open while providing an insurance against drought, pest and economic risks. Although the soils are generally inherently fertile, cultivation of the steep slopes would lead to severe erosion and declining fertility were it not for the woody component of the system. (Fernandes, Oktingati and Maghembe 1984).

The above examples illustrate how trees are nothing new to the small farmer, and the land use planner should therefore start by trying to develop an understanding of how the small farmer perceives the benefits of the trees to the system as a whole and how the existing trees are managed and used. For instance, is there a conscious awareness of the tree benefiting neighbouring crop production, does the farmer manage the tree to reduce its effect on crops and what products does the tree yield? These will act as the starting points for introducing more trees into the system. For instance, where the soil improving qualities of an indigenous tree, such as *Acacia albida*, are known to the farmer to increase crop yields this can be used to illustrate to them the principle of using trees for improved soil fertility. It may then be possible to develop in discussion with the farmers an improved land use package whereby the known indigenous tree is deliberately planted in the farmer's field along with a faster growing exotic species that has been introduced to the farmers as having similar benefits to the known tree. Such a practice is being recommended to farmers in Malawi where they are encouraged to plant *Acacia albida* at 10-15m intervals along the contour marker ridges that run through the fields and to plant *Leucaena leucocephala* in between (see Douglas 1984 and Casey 1983). One word of caution on recommending the planting of indigenous trees, as it's been found that in areas where local foresters are zealous in protecting indigenous species, farmers may be reluctant to plant them for fear that the forestry department will claim them as theirs once they've grown.

### **MANAGEMENT OF TREES**

Trees deliberately planted in and grown with crops will require some form of management to obtain many of the benefits and to avoid adverse effects on neighbouring crops. Seeing how farmers presently manage trees will indicate the types of management practices they are already familiar with and therefore already accept as worthwhile use of their labour. New management practices should therefore, if possible, be introduced as a development of the existing practices rather than something totally new.

### **MULTIPLE USES OF TREES**

Of particular interest are the present uses to which the trees in the farmer's land are being put. This will show which particular needs he/she is trying to meet from the tree component of the farming system. Initially the farmer is more likely to be willing to plant new tree species that have the same uses and will enable those same needs to be better met. In many cases the land use planner may see a need that the farmer has yet to perceive, for instance the need to conserve soil on a sloping field. It may prove difficult to persuade the farmer to plant a contour strip of trees for the sake of a conservation barrier but if the farmer has livestock and is experiencing a shortage of feed it is possible to recommend the growing of a tree or shrub with edible leaves and to suggest that this is grown on contour strips through the crops. In this way the farmer can not only meet the fodder need as he/she sees it but help conserve the soil. The soil conservation benefit being the by product of a land use practice recommended to meet the farmers perceived need.

### **POSSIBLE CONSTRAINTS TO THE USE OF TREES**

An objection raised by many farmers to planting trees is that they don't have enough land to grow both food crops and trees. The agroforestry answer is to grow both together but many agroforestry practices do require that parts of the farm are taken out of crop production and put under trees. For instance strips of trees running through farm land in the practice known as alley cropping will occupy a significant portion of the total farm holding. For the farmer to accept that as a worthwhile use of his/her land, either the value of the products from the tree strips has to outweigh the lost crop production from those strips or the strips have to result in increased crop production on the rest of the farm eg. through the use of the leaves as green manure, so that the total yield from the field is the same or preferably higher.

A major constraint affecting many smallholder farming systems is that of shortage of labour, particularly at key times during the cropping season. Many agroforestry practices are labour intensive and this may work against their adoption unless the periods of labour demand can be fitted into the periods of low labour demand from the other farm activities or unless the benefits of the agroforestry practices are seen by the farmer to justify the extra labour. The small farmer will first and foremost direct his/her labour to the cultivation of the good crops. It is therefore important for the land use planner and research worker to remember that to the farmer the most important component of any tree/crop system is the food crop. This must be borne in mind when designing the management practices and their labour requirements. Applying to the soil as a mulch, the prunings from hedgerows grown for the purpose of supplying green manure, is labour intensive but the initial application can be done just prior to the start of the cropping season when there may be a lull in the labour

demand before the peak of planting time. Subsequent applications can be done during other labour lows. A good mulch should also reduce the labour required for weeding. In a number of countries the rise in the cost of chemical fertilizers has resulted in it now being cheaper for the farmer to employ labour to make compost and cut green manure and apply them to crops than to buy the equivalent nutrients as fertilizer (eg. Douglas 1984).

#### **WHICH TREES?**

Finally a few thoughts on the trees themselves. Ideally what the land use planner wants from the research worker is a selection of tree and shrub species with as wide a range of potential uses as possible and with detailed information on the range of environmental conditions under which these will grow. The trees should be simple to grow, the simplest is if they can be direct seeded or grown from cuttings and preferably not requiring careful raising in nurseries. They should be able to survive poor management and goats, grow quickly and start to show benefits in the first couple of years. Trees that require careful nurturing to maturity, grow slowly and give no returns to the farmer for many years will not be readily adopted even if in the long run they offer many benefits. Furthermore, examples of the recommended trees should already be growing in the area so that farmers can see what they look like, how to manage them and most importantly what they can be used for.

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## AMELIORATION OF SOIL BY TREES - THE WAY FORWARD

R T Prinsley and J I Furtado  
Commonwealth Science Council

A soil of high productivity offers plant roots:

- (1) deep rooting because of many large pores and good movement of soil particles against each other;
- (2) a sufficient water supply due to a high available water capacity;
- (3) optimal gas circulation with the atmosphere because of a high content of stable coarse pores;
- (4) high nutrient reserves, together with a high exchange capacity;
- (5) intensive soil flora and fauna, which regenerate the nutrient pool by mineralising organic matter (Blume, 1985).

Tropical soils vary greatly in type and productivity. Geologically recent soils of volcanic or sedimentary origin are often very fertile. Those derived from older igneous rock and are heavily leached, are acidic and have a low moisture and nutrient-holding capacity.

In general, however, the sudden and heavy rainstorms of the tropics cause leaching of soluble plant nutrients to below the root zone. Many soils, therefore, have a low level of natural potential fertility and are particularly low in N and P. Much of the nutrient content in the crop zone is contained in the vegetation. The level of organic matter in tropical soils is also usually low, most of it breaking down quickly in the warm moist conditions. Many tropical soils also have poor structure, thus reducing their stability under intensive cultivation. In areas of alternating wet and dry seasons, a rapid but short-term release of nutrients is produced, often at the onset of the rains. Heavy rainstorms are also responsible for widespread erosion in the tropics. Additionally, soils with specific 'problems' are common in the tropics, eg saline soils and sandy soils (see 'Amelioration of Soil by Trees' 1986 for descriptions of problem soils).

As described by Anderson in Chapter 2, there is a great contrast between (1) the natural ecosystem where some of the lowest fertility soils support rainforests of massive structure and productivity as a consequence of tight nutrient cycling between vegetation and soil and (2) farming, where nutrient-bearing plant materials are removed for human use, inevitably leading to a reduction in soil fertility.

Farmers in the tropics clearly recognize the importance of soil fertility and conservation. However, in replacing the balanced natural ecosystem with a farm-productive system, either soil fertility is consumed or much labour and high material inputs are required if both high production and soil fertility are to be maintained. Tropical farmers, therefore, face a fertility management choice under current scientific and technical knowledge.

The soil may be 'mined' by continuous cropping and no replenishment of nutrients. Food can then be produced cheaply requiring the use of only very

little expensive support energy. The subsequent decline in fertility results in a reduction of yield leading to an unproductive 'low level equilibrium' which is inefficient in terms of solar energy but very efficient in relation to support energy (Rutherberg, 1971).

Alternatively, the farmer requires high support energies to maintain and increase soil fertility. This results in much more efficient use of solar energy but is expensive in economic terms. This alternative is therefore usually unavailable to the poor farmer in the tropics (Rutherberg, 1971).

The farmer, therefore, searches for a compromise between a solar energy efficient, support energy inefficient highly productive system and a solar energy inefficient, support energy efficient low productive system. One of the major modes of farming used to achieve such a compromise is shifting cultivation where there is a tree/bush fallow. The deep tree roots bring up nutrients that had previously been leached down, and the fallen leaves from these trees enrich the nutrient-depleted, overcropped soil surface, and leached nutrients are thus recycled. Other beneficial effects of trees to the soil fertility are outlined in Chapter 2. However, with increased rates of population growth, increased demand for land has limited those areas where shifting cultivation can be practised. There is not enough land to leave much of it resting and unproductive for long periods of time.

Agroforestry options, however, can combine the characteristics of productive herbaceous cropping systems with the ameliorating effects of tree cover and a perennial root network. This combination provides a multiple cropping system for fuel, food fodder and fertilizer. It also has a stabilizing effect on catchment hydrology and soil erosion. Although the practice of agroforestry is very old, it is a very new science. There is very little available knowledge of soil management techniques in agroforestry as practised until now. There is also little understanding of the mechanisms by which trees improve soil fertility. Both of these are required for the formulation of effective management methods in agroforestry. Methods determined on a predictive mechanistic basis rather than on an empirical basis will facilitate technology transfer to needful farmers and will also reduce the time, space and costs required for conventional plot trials.

Young, in Chapter 5, explains that management practices which control the quantity, quality and timing of decomposition of plant residues are required to maintain soil fertility. These processes of decomposition are discussed further by Swift in Chapter 2. As Young (Chapter 5) points out, different management practices can have different effects on soil processes. The complexity of the effects management practices can have on this poorly understood system can be seen in Figure 1.

Clearly, in order for the farmer to know which management method to use when and in which situation, much scientific research is required to further understand the mechanisms by which trees improve soil fertility and interact with soil biological processes, physical factors and nutrient cycling. This will form the basis of Commonwealth Science Council's project which aims to develop a predictive understanding of how to use trees to reclaim problem soils in agroforestry systems.

## **AMELIORATION OF SOIL BY TREES IN THE TROPICS**

Jose I Furtado<sup>(1)</sup>, R T Prinsley<sup>(1)</sup> and M J Swift<sup>(2)</sup>

Although high insolation and precipitation regimes offer the prospect of high biological production in the tropics in comparison to other climatic zones, a variety of factors both physical and cultural mitigate against its realization. Of particular importance among these are poor and edaphic soil conditions, impoverishment of lands by intensive use over successive generations, inadequate knowledge of plant and animal species especially trees for manipulation by human societies, and inadequacy of technology in the cultural repertoire of human societies to optimise land use and landscape integration. Nevertheless, knowledge about soils, trees and agro-ecological interactions is several millennia old having emerged quite independently in several tropical civilisations. Renewed interest in these interactions emerged over the last 20 years through the initiation of the International Biological Programme (IBP), through our understanding of the limitations of the Green Revolution and extensive agricultural development in coping with human population growth, and through the marginalisation of land by careless agricultural technology. This synthesis endeavours to bring together considerations on the above factors in relation to the amelioration of soil by trees especially in the tropics (Figure 1).

### **Tropical Soils**

Highly productive soils offer plant roots the prospect of deep and easy penetration, access to ground water supply, an environment of good gas circulation, access to nutrient reserves maintained by a high exchange capacity, and an association with soil flora and fauna capable of regenerating nutrient reserves by mineralizing organic matter (Blume 1985). However, tropical soils vary greatly in structure and productivity. While geologically-recent soils of volcanic or sedimentary origin are often highly fertile, those derived from older igneous rocks are heavily leached and acidic, and have a low moisture and nutrient-holding capacity. The high precipitation regime in the tropics causes the leaching of soluble nutrients well below the root zone, so that many soils have low levels of natural fertility especially of N and P, and become acidic. As a consequence, plants have adopted the strategy of containing the nutrients in the biomass in the tropics. Soil infertility or acidity in the tropics may be due to aluminium toxicity, calcium and magnesium deficiency, manganese toxicity and a low cation exchange capacity. It may be overcome by liming or by the planting of acid-tolerant plant species.

(1) Commonwealth Secretariat, Marlborough House, London SW1Y 5HX, England, UK

(2) Department of Biology, University of Zimbabwe, Harare, Zimbabwe

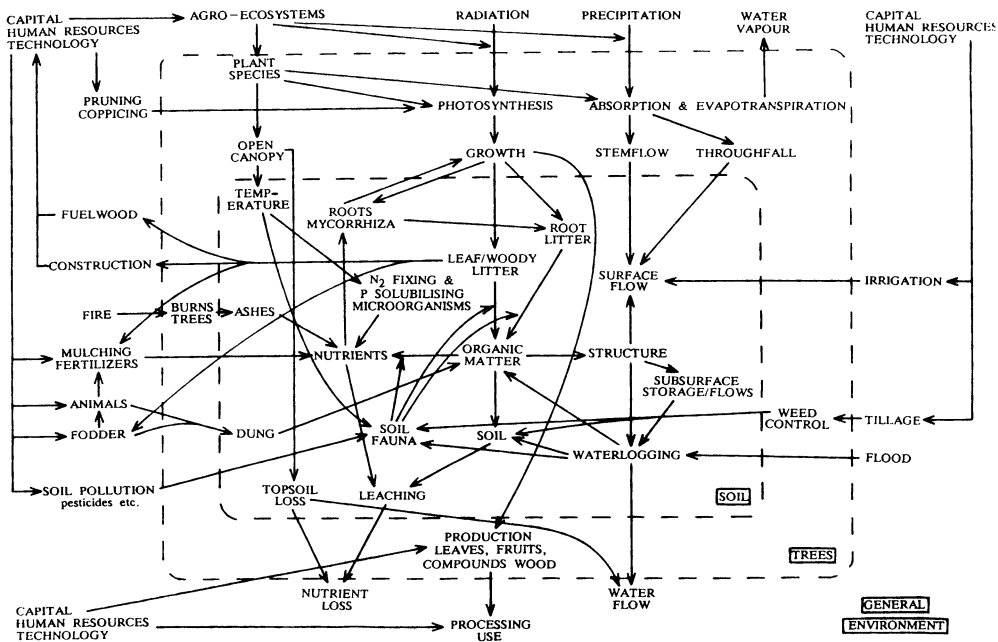


Figure 1: The Amelioration of Soil by Trees showing the interaction between the soil, trees and the general environment.

The high insulation and humidity regimes in the tropics facilitate the rapid breakdown and decomposition of organic matter, so that tropical soils are in organic matter content. This limits the supply of nitrogen and sulphur to plants, lowers the cation exchange capacity, facilitates phosphorus fixation, weakens soil structure, and limits the formation of complexes with micronutrients. The maintenance of organic matter is therefore essential for biological production, either through animal manures or through green manures and mulching. In seasonal climates, nutrients may be released rapidly and for a brief period at the onset of rains, for which plant species must be available to capture available nutrients to optimise production. Anderson (Chapter 2) discusses the efficiency of tight nutrient cycling in tropical rain forests which support a high biomass and productivity, in comparison to farming systems where nutrient-rich plant materials are harvested for human use, thereby leading to the impoverishment of soil fertility. Farmers in the tropics have traditionally recognised the importance of soil fertility and conservation. However, in transforming the natural ecosystems with man-made systems, farmers have either conserved soil fertility or used high material inputs to ensure high production and soil fertility, depending on the availability of labour and technology. Tropical farmers thus face a choice of fertility-management options depending on the level of scientific and technological accultivation of their societies.

Many tropical soils are infertile with low essential nutrients such as nitrogen, phosphorus and sulphur. Symbiotic nitrogen fixation is particularly important in the tropics, not only by rhizobial bacteria but also by non-rhizobial bacteria and blue-green algae. The state of knowledge about the latter is particularly weak. Nitrogen poverty is compensated by the application of fertilizers, by intercropping with nitrogen-fixing plants, or by integrated farming systems involving animal husbandry and/or aquaculture. Phosphorus deficiency is due to phosphorus fixation by iron and aluminium oxides in highly acidic and weathered soils. It is compensated by the application of phosphorus fertilizers or of low-cost phosphorus sources such as rock phosphates, depending on the availability of capital. Sulphur deficiency is widespread in the tropics being found in highly weathered soils, sandy soils and in savanna areas subjected to annual burning.

Tropical soils may be "mined" by continuous cropping without nutrient replenishment. Under these circumstances, organic production may be harvested cheaply with low support energy but will lead to the decline in soil fertility and yields on site, eventually to an unproductive "low level equilibrium" which is inefficient in the use of solar energy but very efficient in the use of support energy (Ruthenberg 1971). Alternatively, the farmer requires high support energy to maintain and increase soil fertility, which in turn results in a more efficient use of solar energy but is expensive. This alternative is usually not available to the poor farmer in the tropics. The farmer thus searches for a farming system that compromises between a solar-energy efficient and support-energy inefficient highly-productive system and a solar-energy inefficient and support-energy efficient poorly-productive system. The shifting cultivation system is one such compromise where there is a tree/shrub and herb/fallow rotation. The shrubs and herbs deplete the soils of nutrients, whereas the trees mobilise the leached nutrients through their deep roots and leaf fall. The beneficial effects of trees to soil fertility are discussed in Chapter 2.

Tropical soils are characterised by a variety of moisture regimes, and exhibit water deficits due to short-term drought. The capacity of the soil to retain water and to supply it to plants is a critical factor for tropical agriculture. Droughts reduce yield, and may be overcome by protecting the soil surface with

mulches and/or a continuous canopy. Many traditional farming systems show sound management alternatives for conserving soil water supply to plants.

Tropical soils are susceptible to erosion when exposed to the high precipitation regime, primarily because of their poor structure. The extent of soil erosion in the tropics is increasing because of extensive deforestation, overgrazing on pasture lands, and poor use of shifting cultivation on steeply sloping lands. Contour planting, the use of trees on slopes and/or protecting the soil by plant residues or canopy cover can enhance soil conservation.

Tropical soils are marked by special edaphic conditions, such as acid sulphate, saline or peat conditions. These pose special problems to the amelioration of soil by trees and are usable for biological production under careful management prescriptions.

### **Biota Especially Trees**

Plant and animal species can be used potentially to ameliorate soil by a variety of combinations. Although some plants such as *Acacia* and *Casuarina* are useful for ameliorating acidic soils, knowledge about plant species is in its infancy in relation to such manipulations for various soil types. In the choice of plant species, it should be noted that trees have a nutrient conservation strategy superior to shrubs and herbs, and that monocotyledons are superior to dicotyledons in this respect. Furthermore, plants through their architecture have differing impacts on light extinction and photosynthesis, interception of precipitation and on protection of soil. Most plant species used in agriculture are species belonging to the early successional phases in community structure, and have been selected for their rapid growth characteristics. These species are low in secondary compounds and are therefore susceptible to pest infestations. In contrast, plant species belonging to the late successional phases in community structure are rich in secondary compounds, and are therefore less susceptible to pest infestations. There is a clear need for selecting species for intercropping and rotational cropping that will ameliorate soils in relation to various dimensions of soil conservation. Selection of species may be extended further for integrated farming coupling land to water.

### **Agro-ecological technology**

Agro-ecological techniques can manipulate the combination of plant species over space and time, the integration of animal species and the coupling of land to water as in integrated farming systems. Each step in the technology towards integrated farming systems requires a measure of cultural pre-adaptation, and the expenditure of capital, labour and human skills. Agro-ecological options can combine the characteristics of biological production with those of soil and water conservation, as in the combination of herbaceous plants with trees in agroforestry systems. Such combinations facilitate multiple outputs as uses such as for food, fuel, fibre, fertilizer and soil stabilization. Although the traditions of agro-ecology are old, the science is relatively new especially of polyculture systems in the tropics, since much of the research effort over the past 100 years or so has been focused on the dynamics of monoculture systems. Species combinations can be supplemented by chemical, mechanical and physical manipulations, all of which are expensive and demanding on human skills. Young (Chapter 5) discusses management practices which control the quantity, quality and timing of organic decomposition required to maintain soil fertility; while

Swift (Chapter 2) discusses further the complexity of the decomposition processes. The complex relationship between agro-ecological management practices and soil fertility (Figure 1) is poorly understood. Further scientific research and technological development (R&D) is needed to elucidate these relationships so that the farmer may choose the appropriate management system for use in relation to the combination of species and the kinds of soils at critical time sequences. Such a focus constitutes the basis of a cooperative project developed through the catalytic action of the Commonwealth Science Council.

In examining the impact of trees on soil in various agro-ecosystems, it is pertinent to note four system properties that need to be optimised from traditional agro-ecosystems to advanced ones (Conway 1984):

- Productivity or desired output of the system measured in terms of crop yield or net income.
- Stability or short-term homeostasis of the system measured in terms of the coefficient of variation of yield or net income.
- Sustainability or ability of the system to persist through repeated stress or major perturbations like deteriorating soil structure, growing pollution or the sudden appearance of a new pest or disease. This property is difficult to identify and measure, although it may be observed after a system has collapsed.
- Equitability or the pattern of distribution of the products or benefits of the system among human individuals interacting with it, and is easy to measure in the formal economy as a function of capital, land and/or other resources but is difficult to measure in the informal economy, in terms of non-fiscal incentives or rewards, or at the level of self-actualization.

<u>System properties</u>	<u>Productivity</u>	<u>Stability</u>	<u>Sustainability</u>	<u>Equitability</u>
Gradations of Agro-ecosystems:				
A (Traditional)	Low	Low	Medium	Medium
B (Green Revolution)	High	Low	Low	Low
C (Advanced Green Revolution)	High	High	Low	Low
D (Advanced)	High	Medium	High	High

### The Problem for Research

The response of soils to trees will be assessed by the measurement of a standard selection of soil properties and processes, related to nutrient cycling, soil physical factors and soil biological processes.

- (1) **Nutrient Cycling:** The two factors need to be measured in association with nutrient cycling, litter decomposition and the status of soil organic matter.
- (2) **Soil Physical Properties:** Four soil physical properties need to be measured: soil water, soil structure, soil stability and soil temperatures.
- (3) **Soil Biological Properties:** Four biological characteristics of the soil will be measured as indices of soil amelioration: microbial biomass, nitrogen-fixing organisms, mycorrhizal activity and soil fauna.

The experimental design within which the above properties will be measured is as follows:

- that it permits the investigation of specific hypotheses on the effects of trees on particular soil properties;
- that it is appropriate in terms of choice of trees and land-use systems to the area;
- that it is appropriate to the soil ameliorative requirement of the area;
- that it will achieve standardisation of methods to enable exchange of data between sites;
- that wherever possible it can incorporate options on choice of trees, mixture of trees and mixtures of farming systems.

The 'problem' soils chosen represent the priority developmental needs of Commonwealth countries:

- soils of low fertility - both naturally and due to nutrient exhaustion;
- sloping lands with erosive risk under dense population pressure;
- saline and alkaline soils;
- semi-arid lands.

Among the various agro-ecosystems appropriate for experimentation on soil amelioration of these 'problem' soils, alley-cropping has been chosen because it lends itself to experimental manipulation, has wide applicability and has proven potential in many areas.

The objectives of the project are:

- To build up a model of plant-soil nutrient cycling under tree-crop mixtures.
- To identify and demonstrate successful agroforestry systems of soil amelioration by trees for the area in which the experiment is carried out.

The major variables measured will include plant species, spacing (between and within rows) and management (pruning etc). In the experimental design, there will be unvegetated control plots, tree plots, crop plots and tree-crop interfaces as well as alley cropping trials. The tree plots will be used for species selection as well as for the study of organic matter and nutrient cycling of the tree component. Trees will be managed as they would in the alley cropping situation. The crop plots will be used for crop yield determinations as well as for the study of organic matter and nutrient cycling under the crop component. Detailed measurements along transects between trees and crop will be made. Alley cropping trials will consist of:

- . 3 x between-row tree spacings
- . 4 x within-row tree spacings
- . 8 x tree species

The whole design, without replication, could be contained on a site of four hectares. Other possible designs, eg split plots, fans, and randomised block designs, could be considered. Organic matter and nutrient cycling studies would be made on selected blocks, besides basic measurements (eg litter and pruning biomass, soil organic matter) on all plants. Further features of the design could be developed on the basis of the recommendation published by ICRAF (eg Systematic Designs ICRAF Working Paper No. 12).

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# Amelioration of Soil by Trees

A review of current concepts and practices

The utilization of marginal and degraded lands, often associated with regions of high population densities, has high international priority for food and fuel production, erosion control and conservation. It is commonly believed that the enhancement of fertility of these soils can be achieved by use of trees, particularly by manipulation of associated soil biological processes. In this volume, this belief is subject to initial scrutiny and various proposals are made for research to investigate the links between trees and soil fertility.

This volume represents the collection of papers presented at the Commonwealth Science Council's Agroforestry meeting in India in March 1986 for Africa and Asia.

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